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Conceptual Evaluation of Ground-Water Flow and Simulated Effects of Changing Irrigation Practices on the Shallow Aquifer in the Fallon and Stillwater Areas, Churchill County, Nevada

Water-Resources Investigations Report 99-4191

Prepared in cooperation with the
BUREAU OF RECLAMATION

science for a changing world

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By Nora B. Herrera, Ralph L. Seiler, *and* David E. Prudic

U.S. GEOLOGICAL SURVEY

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Carson City, Nevada
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information contact:

District Chief
U.S. Geological Survey
333 West Nye Lane, Room 203
Carson City, NV 89706–0866

email: GS-W-NVpublic-info@usgs.gov

http://nevada.usgs.gov

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CONVERSION FACTORS, VERTICAL DATUM, AND WATER-QUALITY ABBREVIATIONS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
acre-foot per acre per year (acre-ft/acre/yr)	0.3048	meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1	meter per meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per year (ft/yr)	0.3048	meter per year
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per day (gal/d)	3.785	liter per day
gallon per minute per foot (gal/min/ft)	0.2070	liter per second per meter
inch (in.)	25.40	millimeter
inch per day (in/d)	25.40	millimeter per day
inch per year (in/yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton (t)	0.9072	megagram

Temperature: Degree Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)] + 32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556 (°F - 32).

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called “Sea-Level Datum of 1929”), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Water-quality units used in this report:

µS/cm	microsiemens per centimeter
mg/L	milligrams per liter
µg/L	microgram per liter

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ABSTRACT

The Newlands Project was built in the early 1900’s to supply water for irrigating land in the Carson Desert near Fallon, Nevada. Recently, environmental groups and the U.S. Fish and Wildlife Service have made efforts to purchase agricultural water rights in the area. Local residents who use the shallow aquifer as a water supply are concerned because of potential effects on the quantity and quality of domestic water and of recharge reduction caused by the purchase of agricultural water rights. In December 1996, the U.S. Geological Survey began a study with the Bureau of Reclamation to estimate potential effects on water levels, flow, and water quality in the shallow aquifer from changing irrigation practices in the Newlands Project area.

The shallow aquifer generally extends from the water table to a depth of 50 feet below land surface. The aquifer is characterized by abrupt changes in lithology and water quality, both vertically and horizontally. The abrupt changes in lithology result from a complex mixture of river-channel, delta, floodplain, shoreline, lakebed, and sand-dune deposits that form the shallow aquifer. In irrigated areas, ground-water flow is controlled by location of canals and drains and by application of water onto fields. Water levels in the aquifer fluctuate in response to the release of water into canals and when fields are irrigated. Water levels fluctuate seasonally between 2 feet and 6 feet below land surface with highest water levels during the irrigation season and lowest water levels during winter.

The potential effects of reducing recharge to the shallow aquifer were estimated by using numerical models of ground-water flow in two representative areas, each about 9 square miles (5,760 acres). The first area selected is just south of Fallon, Nevada, where vertical gradients in the unconsolidated alluvial deposits indicate primarily lateral flow through the sedimentary aquifers. The second area selected is near Stillwater, Nevada, where vertical gradients indicate upward flow through the sedimentary aquifers. The models were used to simulate the general timing and duration of recharge for a typical year in both areas. Results for a typical year were then used to determine the effects of reduced recharge from canals and fields on water levels, flow, and water quality caused by changing irrigation practices.

Each model was calibrated to incorporate typical irrigation practices during a normal year. The normal year was divided into six periods to represent changing irrigation practices and repeated for 5 years during calibration because exact initial conditions were not known. The 5-year period was sufficient to attenuate effects caused by uncertainties associated with initial conditions. During calibration, modeled values were adjusted within acceptable limits until simulated water levels and gradients approximated observed levels and gradients, and inflow and outflow approximated estimated rates. Results from the model simulations indicate that canal seepage and water applied to fields (applied irrigation) account for most of the recharge in the modeled areas. In the Fallon area, discharge is primarily by evapotranspiration and seepage to drains. In the Stillwater area, evapotranspiration is the dominant form of discharge.

The model was run with five different hypothetical scenarios in each area to estimate the possible effects on ground-water levels and flow in the shallow aquifer due to changing irrigation practices. In each scenario, the quantity of water for applied irrigation was reduced from a normal irrigation season. In two scenarios, recharge from applied irrigation was reduced 50 percent by uniformly decreasing the rate of water applied to fields or by maintaining the rate and shortening the irrigation season. In two other scenarios, applied irrigation on a half section of land (total area of 320 acres) was removed in the center of each of the modeled areas with one scenario assuming continued deliveries in the canal and the other assuming abandonment of a section of the canal. Because not all land in a half section is irrigated, irrigated areas ranged from 275 acres in the Stillwater area to 292.5 acres in the Fallon area. For the last scenario, all recharge from applied irrigation was eliminated, while recharge from precipitation and water deliveries in canals were maintained. Although maintaining water in lateral canals is unlikely if all irrigation in an area ceases, the scenario provides an estimate of the effects of eliminating recharge from applied irrigation over an area larger than a half section.

The model was run for each scenario for a period of 5 years, a length of time sufficient for the model to reach a dynamic equilibrium. Water-level declines for all scenarios averaged 1.1 feet or less in the Fallon area and 1.4 feet or less in the Stillwater area. The largest seasonal water-level declines of about 10 feet were produced near canals when the irrigation season was shortened. When water was maintained in the canals, maximum declines in areas distant from canals ranged from 2.6 to 7.1 feet.

The greatest decease in the ground-water budget was associated with reduction of canal seepage and recharge of applied irrigation during a shortened irrigation season. Ground-water budgets in the modeled areas decreased less than 5 percent when irrigation on a half section of land was eliminated. In the Stillwater area, net upward flow increased in some scenarios; however, net upward flow was negligible in all simulations compared with other components of the budget.

Estimates of salt loads from mass-balance calculations suggest that, for a typical irrigation season, removal of a half section of land from irrigation will result in only small changes in annual salt load to the aquifer. In the Fallon and Stillwater areas, applied irrigation accounts for 64 and 57 percent, respectively, of the annual salt load to the shallow aquifer. If water deliveries to lateral canals remain unchanged, irrigation reduction in the Fallon and Stillwater areas is likely to lower the average salinity of the shallow ground water. Removing canals from service will affect seepage from canals, which likely will cause dissolved-solids concentrations to increase in wells for which canal seepage is a principal source of water supply.

INTRODUCTION

The Newlands Project was created by the passage of the Reclamation Act by the U.S. Congress in 1902, and was originally intended to facilitate irrigation of more than 200,000 acres of land near Fallon and Fernley, Nevada (fig. 1). The Truckee Canal was excavated to divert water from the Truckee River to the Carson River drainage and at the same time to provide water for irrigation of land between Fernley and Lahontan Reservoir. Delivery of water to farmers in the Fallon area (Carson Division of the Newlands Project area) began in 1906. Construction of Lahontan Reservoir on the Carson River was completed in 1915. Since 1915, some water from the Truckee River has been diverted to Lahontan Reservoir through the Truckee Canal. Total water righted acreage in the Carson Division consists of 67,820 acres of which 52,800 acres was irrigated in 1994, a year when storage in Lahontan Reservoir was below normal (Bureau of Reclamation, 1994, p. 6).

The construction of a network of canals in the Fallon area and the delivery of water for irrigation of fields caused the ground-water table to rise (Seiler and Allander, 1993, p. 10). Prior to initiation of the Newlands Project, depth to ground water was less than 5 ft below land surface along active channels of the Carson River, and was more than 25 ft below land

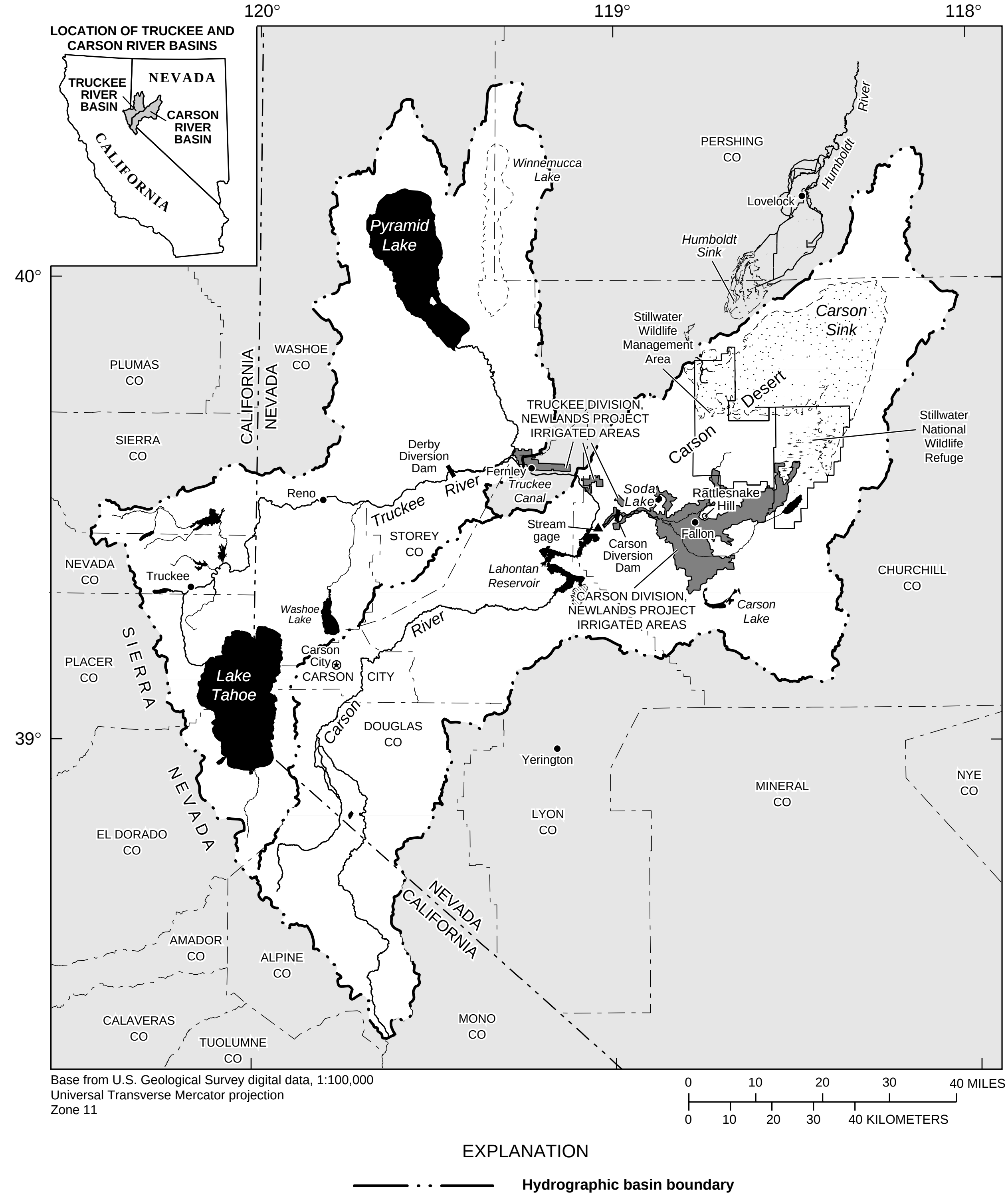


Figure 1. Location of Carson and Truckee River Basins and Newlands Project area near Fallon, Nevada.

surface in large areas northwest and northeast of Fallon. As ground-water levels rose beneath fields, drains were installed which lowered nearby water levels and prevented waterlogged fields. Consequently, in 1992 depth to ground water was more uniform, ranging from 5 to 10 ft below land surface beneath much of the irrigated area (Maurer and others, 1996, p. 33). The water table rose between 25 ft and 40 ft near Soda Lake, northwest of Fallon, after irrigation began and became stable after 1930 (Seiler and Allander, 1993, p. 11). This suggests that ground water near Soda Lake reached a new equilibrium after 25 years. In other areas, the time required to reach a new equilibrium was probably less because of a greater density of canals and drains and because the water table initially was closer to land surface.

Conservation-based Operating Criteria and Procedures (OCAP) for the Newlands Project were first instituted in 1967 and were designed to ensure coordinated operation of the Carson and Truckee Rivers (Bureau of Reclamation, 1994, p. 7). OCAP was revised in 1972 to limit diversions from the Carson and Truckee Rivers and again in 1988 to provide incentives for conservation and to eliminate any wasteful project operations (U.S. Department of Interior, 1988; Bureau of Reclamation, 1994, p. 8). The recent passage of laws to protect endangered species point to the growing conflict among different users for the limited quantity of water available in the region.

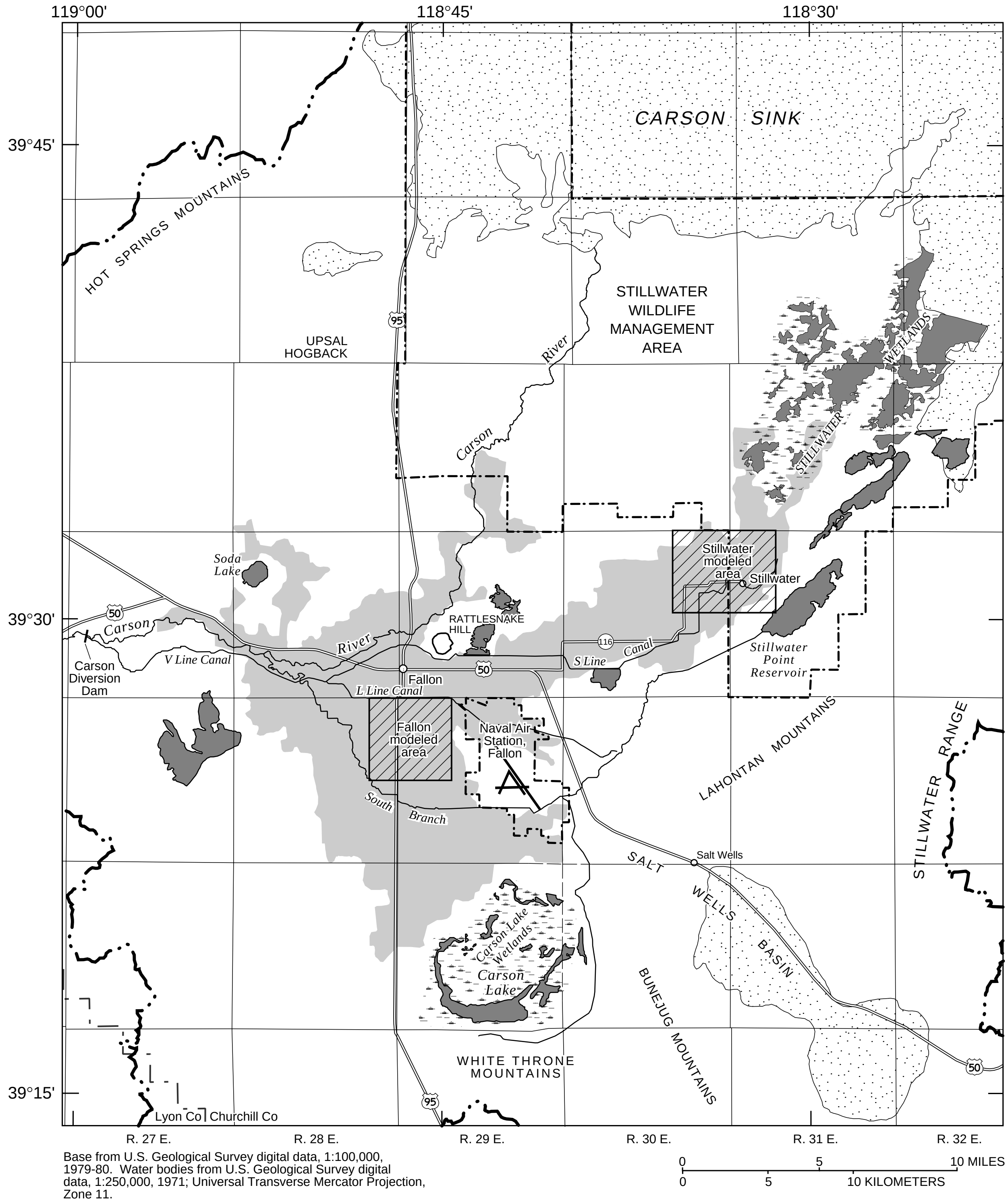
The passage of Public Law 101-618 in 1990 required the study of the feasibility of improving the conveyance efficiency of the Newlands Project facilities to an average level of 75 percent or greater by the year 2002. This law also required the Secretary of the Interior to "report on the social, economic, and environmental effects of a water rights purchase program authorized …" for the protection of Lahontan Valley wetlands (U.S. Fish and Wildlife Service, 1993). The purpose of this law is to increase flows to Pyramid Lake to avoid the extinction of the endangered Cui-ui and threatened Lahontan cutthroat trout, and to wetland areas in the region to maintain a habitable environment for wildlife.

The purchase of agricultural water rights from farmers within the Newlands Project area will decrease the quantity of water for applied irrigation, which likely will decrease the quantity of recharge to ground water and return flow to drains. The reduction of recharge could, thus, impact the wells that pump shallow ground water for domestic supply. Maximizing the efficiency of the Newlands Project will increase the quantity of water available to meet demands for project water, as well as for other purposes. However, increasing the conveyance efficiency likely will result in a decrease in recharge to ground water. Decreasing recharge to ground water may cause a decrease in seepage to drains that potentially could affect the wetlands because drains are a major source of water for the wetlands (Bureau of Reclamation, 1994, p. 1). The U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation, began a study in Dec. 1996 to estimate the potential effects of reductions in irrigation applications on recharge and flow of shallow ground water in the Newlands Project area.

Purpose and Scope

The purpose of this report is to examine responses of shallow ground-water flow within the sedimentary shallow aquifer to possible changes in irrigation practices. Numerical models of ground-water flow were used for the analysis. Detailed modeling of ground-water flow over the entire Newlands Project area is beyond the scope of this study. Consequently, within the Newlands Project area, two representative areas were identified where cessation of irrigation from small parcels (up to 320 acres) could be evaluated in terms of potential changes in ground-water levels and flow. These areas, each about 9 mi^2 (5,760 acres), were selected on the basis of having large canals and drains as boundaries along at least two sides. The first area selected is just south of Fallon (fig. 2) where vertical gradients in the unconsolidated alluvial deposits indicate mostly lateral flow through the sedimentary aquifers. The second area selected is near Stillwater (fig. 2) where vertical gradients indicate upward flow through the sedimentary aquifers.

Simulated irrigation scenarios were designed assuming that the overall quantity of water available to recharge the shallow ground water from water applied to fields (hereafter referred to as applied irrigation) in the Fallon and Stillwater areas would be reduced. Numerical models were used to simulate possible changes in irrigation practices and the resultant potential changes in the quantity and quality of shallow ground water. Ground-water levels, flux from deeper alluvial aquifers, applied irrigation, canal seepage, return flow from septic systems, precipitation, withdrawals from wells, seepage to drains, evapotranspiration, and hydraulic properties of the unconsolidated alluvium were considered in the development of the



EXPLANATION

Irrigated land—From Bureau of Reclamation digital data (Charles Johnson, Bureau of Reclamation, written commun., 1993)

Wetlands

Discharging playa — From Glancy and Katzer (1975, pl. 1)

Hydrographic-area boundary—From Rush (1968)

Figure 2. Irrigated farmlands in Carson Division of Newlands Project area, selected irrigation canals (V, S, and L lines), irrigation reservoirs, wetlands, and modeled areas near Fallon and Stillwater, Nevada.

numerical models and in the analysis presented in this report. Results of the simulations have been used to make general predictions about changes in water quality associated with irrigation reduction. Insufficient information was available to thoroughly calibrate each numerical model, thus, the numerical models were not designed to exactly replicate actual flow everywhere in shallow ground water in each area.

Data collection began in Dec. 1996 and continued through Aug. 1997. Specific canal and drain locations were identified. Width and depth measurements were made of the canals and drains and of water depths in them. The area of irrigated land within each study area was estimated. Streamflow measurements also were made at specific locations within the study areas on two occasions to help verify numerical-model results.

Location and General Features

The Newlands Project area near Fallon is within the Carson Desert, which is a large, flat plain that extends northeastward from Lahontan Reservoir to the Carson Sink (fig. 1). The Carson Sink is the terminus for the Carson River and, during extended wet periods, it also receives water discharging from the Humboldt Sink. The floor of the Carson Desert lies at an altitude of about 3,900 ft. Climate in the Carson Desert is controlled primarily by the Sierra Nevada, which provides a rain shadow effect to the east. Precipitation at the Fallon Agricultural Experiment Station just south of Fallon averaged 5.3 in/yr from 1961 to 1990 (Owenby and Ezell, 1992). Potential evaporation rates are much greater than precipitation and average 60 in/yr (Bureau of Reclamation, 1987). Temperatures range from an average minimum of 17^{o}F to an average maximum of 90^{o}F (Maurer and others, 1996, p. 4).

Agriculture is the primary land use in the Fallon area, and is a significant part of the local economy. Alfalfa is the predominant crop and accounts for 53 percent of the crops grown on irrigated land. Pasture and other forage crops account for 23 percent whereas cereal and vegetable crops account for the remainder (Bureau of Reclamation, 1992b, p. 37).

The Newlands Project area generally is irrigated from Apr. 1 through Oct. 31. Most water used for irrigation is released from Lahontan Reservoir. This water is delivered to irrigated fields through a series of canals and storage reservoirs. Water is distributed to fields through lateral and individual farm canals that are operated by the farmers. Most fields are irrigated by controlled flooding, and excess water leaves the area through a system of surface drains that also collect seepage from shallow ground water.

Acknowledgments

The authors wish to thank Carol Grenier (Bureau of Reclamation, Carson City, Nev.) and Willis Hyde (Truckee Carson Irrigation District, Fallon, Nev.) for information they provided on the canal and drain system for the Newlands Project. The authors also thank Alan Welch, Michael Lico, David Berger, James Wood, and Douglas Maurer (all from U.S. Geological Survey, Carson City, Nev.) for field assistance and in the conceptualization, design, and analyses of this study.

HYDROGEOLOGIC FRAMEWORK

The geology and hydrology of the Carson Desert, as well as changes in the hydrology brought about by the development of the Newlands Project area in the early 1900’s, control ground-water flows. The geology and hydrology of the Carson Desert previously has been described by Morrison (1964), Glancy (1986), and Maurer and others (1996) and a detailed discussion will not be presented herein. The following sections briefly summarize the geology and hydrology of the Carson Desert as they affect ground-water flow in the Carson Division of the Newlands Project area and in particular, the two areas selected for numerical models.

Geologic Setting

The sediments that underlie the Carson Desert are composed of multiple layers of alluvium and alluvial-fan deposits, and lacustrine sediments that include beach and eolian deposits. The Carson Desert has been receiving sediments since at least the late Tertiary time, 17 Ma (million years ago), when ongoing extensional block faulting began that created the basin- and range-topography of today (Maurer and others, 1996, p. 6). The older sediments are buried beneath Quaternary sediments that were deposited during the Pleistocene, 1.6 Ma to 10 ka (thousand years ago), and Holocene, 10 ka to present. Quaternary volcanic activity was rare in the Carson Desert, and only limited evidence of its occurrence can be found. The most noteworthy volcanic episode was the formation of a volcanic cone

(Rattlesnake Hill) approximately 1 Ma. The cone subsequently was eroded and in part buried by sediments (Morrison, 1964, p. 23).

Several times during the Pleistocene, a large lake (ancient Lake Lahontan) formed under the influence of glacial climates (Maurer and others, 1996, p. 7). At its highest stand, the ancient lake covered much of northwestern Nevada and was more than 500 ft deep in the Carson Desert (Morrison, 1991, p. 288). Thick clays were deposited in the deeper parts of the ancient lake and sand and gravel beaches and bars formed along the shoreline (Morrison, 1964). Deltas were prominent in the western part of the Carson Desert where the Carson River flowed into the ancient lake. Thus, sediments generally are coarser west of Fallon and become finer to the northeast and southeast of Fallon.

Ancient Lake Lahontan began drying up about 14 ka (Benson, 1991, p. 115) and by 7 ka it had almost dried up (Morrison, 1991, p. 300). Several shallow lakes have formed temporarily since that time. During dry periods (similar to the last 7 ka), when only shallow lakes occupied parts of the Carson Desert, large sand-dune and sand-sheet complexes formed and the Carson River eroded numerous channels through previously deposited sediments as deltas moved eastward across the desert floor (Morrison, 1964; Maurer and others, 1996).

Consequently, the sedimentary deposits that underlie the Carson Division of the Newlands Project area consist of interbedded and intertonguing deposits of clay, silt, and sand that record many expansions and contractions of lakes in the area.

The most recent deposits (post ancient Lake Lahontan) are the Turupah (from 7 to 4 ka) and Fallon (from 4 ka to present) Formations. The Turupah Formation consists of eolian sand as much as 30 ft thick and local alluvial sand as much as 15 ft thick (Maurer and others, 1996, p. 15). The Fallon Formation, which overlies the Turupah Formation consists of eolian sand, alluvial and deltaic sand and silt, and shallow-lake sediments (Maurer and others, 1996, p. 15). These deposits overlie deposits of the Sehoo Formation, which formed during the last three deep lake cycles of ancient Lake Lahontan (40 ka to about 7 ka; Maurer and others, 1996, p. 14). The upper member of the Sehoo generally is 1 to 5 ft thick, and is more frequently a sand, in particular west and north of Fallon. The lower member consists mostly of clay and silt in the lowlands near Fallon and Stillwater and is as much as 30 ft thick (Maurer and others, 1996, p. 14).

Exposed channel deposits of the Fallon Formation were mapped by Morrison (1964) and Dollarhide (1975) and collated by Maurer and others (1996, pl. 3). These deposits consist of sand and pebbly sand that depict bed deposits from former channels of the Carson River (Morrison, 1964, p. 86). Locally, these former channels cut through older sediments and may provide preferential flow paths for shallow ground water. The former channels also could provide vertical connections between sand units where they have eroded through older lake clays (Maurer and others, 1996).

Hydrologic Setting

Surface Water

Prior to the development of the Newlands Project, most surface water flowed unregulated to the area by way of the Carson River, which discharged alternately to Carson Lake and to the Carson Sink (fig. 1). Since 1915, surface-water flow has been regulated at Lahontan Reservoir. The reservoir has a maximum storage capacity of 317,000 acre-ft (Bureau of Reclamation, 1992b, p. 35). Releases from the reservoir averaged 370,000 acre-ft annually between 1975 and 1992 (Maurer and others, 1996, table 1).

Surface-water flow downstream from the reservoir has been controlled for 90 years by irrigation diversions for the Newlands Project. Surface water is distributed to an estimated 1,500 farm headgates of the Newlands Project through a complex distribution system of approximately 70 mi of main canals and 300 mi of lateral canals (Bureau of Reclamation, 1986, p. I-4). The canals generally are kept free of weeds. Only about 25 mi of the canals and laterals are lined with concrete (Carol Grenier, Bureau of Reclamation, oral commun., 1993). Water available at the farm headgates averaged 170,000 acre-ft annually between 1975 and 1992 (Maurer and others, 1996, table 1).

Irrigation return flow is routed through about 350 mi of open drains (Bureau of Reclamation, 1986, p. I-4). These drains also route seepage from shallow ground water to the Carson River, which discharges to the Carson Sink and to wetlands in the Stillwater Wildlife Management Area and Carson Lake (fig. 1). Estimated outflow to the Carson Sink and to the wetlands averaged 170,000 acre-ft annually between 1975 and 1992 (Maurer and others, 1996, table 1). Operational spills, overland flow and seepage from the shallow aquifer make up the outflow measured in surface drains. Flow in the drains is distributed to wetlands and entitled water rights outside of the irrigated agricultural areas. Approximately 57 percent of this flow discharges from the shallow aquifer (Chambers and Guitjens, 1995).

The excavation of drains was necessary to keep many fields from becoming waterlogged. The drains are important also because they control water levels in shallow ground water throughout much of the Newlands Project area. Many drains are in close proximity to unlined main or lateral canals, which could result in canal water seeping into the nearby drains (Bureau of Reclamation, 1986, p. IV-44). In contrast to the canals, the drains usually are not maintained and can be overgrown with weeds.

Ground Water

Ground water occurs at shallow depth beneath much of the Carson Desert. However, the area generally is unfavorable for large supplies of good quality ground water (Morrison, 1964, p. 117). Few principal aquifers have been delineated in the Carson Desert (Glancy, 1986). On the basis of depths and water chemistry, three aquifers have been delineated in the sedimentary deposits—shallow (water table to depth of 50 ft below land surface), intermediate (depths of 50 ft to 500 to 1,000 ft), and deep (depth greater than 500 to 1,000 ft). A fourth aquifer is a basalt from the volcanic cone of Rattlesnake Hill. The basalt extends from just south of Fallon to 6 mi northeast of Rattlesnake Hill, and varies in thickness from a few feet near its edge to at least a few thousand feet near Rattlesnake Hill.

More than 5,000 wells have been drilled into the sedimentary aquifers (Maurer and others, 1996, p. 2). Few of these wells yield sufficient quantity and quality of water for irrigation or uses other than domestic. Most wells are drilled to shallow depths less than 150 ft and are used for domestic supply in the rural areas. The basalt aquifer is remarkable in that it is highly permeable and contains water of low salt content (Glancy, 1986). This aquifer is used for a water supply by the City of Fallon; the Naval Air Station, Fallon; and the Fallon Paiute-Shoshone tribes.

Each sedimentary aquifer can consist of many beds of permeable sand and gravel that are interbedded complexly with beds of less permeable silt and clay. The permeable beds can act independently from other permeable beds over short time periods but the beds are interdependent over longer time periods because of the interconnected nature of the sediments (Glancy, 1986, p. 6). Locally, the shallow, intermediate, and deep aquifers could be divided into many aquifers but these aquifers would be difficult to correlate between locations. Thus, the shallow, intermediate, and deep aquifers are each a collection of aquifers that provide continuity over much of the Carson Desert.

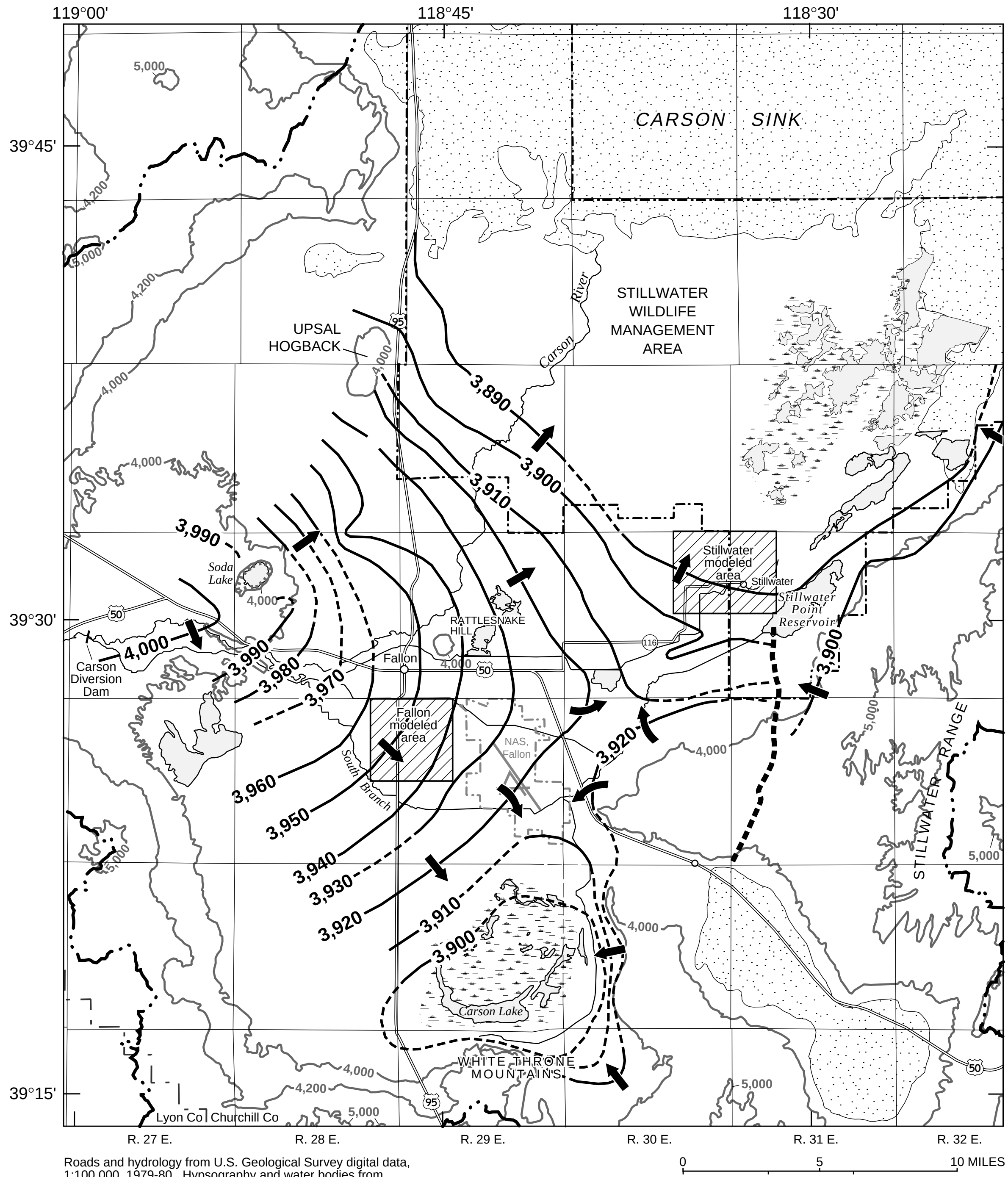
Deep flow of geothermal water has been reported in the Soda Lake/Upsal Hogback area (Olmsted and others, 1984), in the Stillwater area (Olmsted and others, 1975; Morgan, 1982), near Carson Lake (Katzenstein and Bjornstad, 1987), and near Salt Wells (Geothermal Resources Council, 1985). Total flow into the shallow, intermediate, and deep aquifers could be as much as 4,000 acre-ft/yr (Maurer and others, 1996, p. 47). This flow includes 1,500 acre-ft/yr in the Soda Lake/Upsal Hogback area and between 1,300 acre-ft/yr and 2,500 acre-ft/yr in the Stillwater area (Olmsted and others, 1975; Morgan, 1982, p. 88).

SHALLOW AQUIFER

The shallow aquifer consists of sediments of the Fallon, Turupah, and Sehoo Formations (Maurer and others, 1996, p. 37). The aquifer is characterized by abrupt changes in lithology and water quality, both vertically and horizontally (Glancy, 1986, p. 58-59). The abrupt changes in lithology result from a complex mixture of river-channel, delta, floodplain, shoreline, lakebed, and sand-dune deposits that form the shallow aquifer (Maurer and others, 1996, p. 38). Generally, these sediments in the shallow aquifer are coarser and more permeable west of Fallon and become finer-grained and less permeable to the east.

Ground-Water Flow

The general direction of ground-water flow in the shallow aquifer primarily follows the general direction of flow in the Carson River (northeast to the Carson Sink) and flow in the South Branch of the Carson River (southeast to Carson Lake; fig. 3). Horizontal hydraulic gradients range from about 6 ft/mi toward Carson Lake and about 9 ft/mi toward the Carson Sink (Seiler and Allander, 1993, p. 17). The average horizontal hydraulic gradient of the unconfined zone near Stillwater is about 5 ft/mi (Morgan, 1982, p. 45). Upward vertical hydraulic gradients were observed in the Stillwater area and averaged 0.04 ft/ft (Morgan, 1982, p. 50). Higher water levels in wells in the shallow aquifer compared with water levels in wells in the intermediate



Roads and hydrology from U.S. Geological Survey digital data, 1:100,000, 1979-80. Hypsography and water bodies from U.S. Geological Survey digital data, 1:250,000, 1971
Universal Transverse Mercator Projection, Zone 11

EXPLANATION

Discharging playa — From Glancy and Katzer (1975, pl. 1)

3,910 **Water-table contour** — Shows altitude of water table, 1992. From Seiler and Allander (1993, pl.1). Dashed where uncertain. Contour interval 10 feet. Datum is sea level

Zone of faulting thought to control water-table configuration — From Greene and others (1991)

General direction of ground-water flow — From Seiler and Allander (1993, pl.1)

Hydrographic area boundary — From Rush (1968)

4,200 **Topographic contour** — Shows altitude of land surface. Contour interval 1,000 feet, with supplemental contour at 4,200 feet. Datum is sea level

Figure 3. Water-level altitude and general direction of ground-water flow in shallow aquifer, vicinity of Carson Division of Newlands Project area, Fallon, Nevada. Modified from Maurer and others, 1996, figure 10.

aquifer were reported for a large area west of Fallon and to a lesser extent to the south and east of Fallon by Glancy (1986, p. 55-56). Downward vertical gradients of about 0.1 ft/ft were estimated near Soda Lake and north of Rattlesnake Hill and an upward gradient of 0.16 ft/ft was estimated at the Naval Air Station, Fallon by Maurer and others (1996, p. 42).

Shallow ground-water flow is controlled locally by the location of canals and drains and by application of water onto fields (Lico and others, 1987). Water levels in the aquifer fluctuate in response to the release of water into canals and applied irrigation but the amplitude of fluctuations decreases with increasing distance away from irrigated areas (Glancy, 1986, figs. 18–21). Near irrigated areas, water levels fluctuate seasonally between 2 ft and 6 ft below land surface with highest water levels during the irrigation season and lowest water levels during winter. The decline in water levels during the winter generally is limited to the depth of drains, which have been excavated between 4 ft and 8 ft below land surface over most irrigated areas (Bureau of Reclamation, 1992a, p. 12) but can be as much as 20 ft in some areas. Water levels in areas distant from stream channels and irrigation fluctuate less than 2 ft seasonally (Glancy, 1986, p. 39).

Recharge and Discharge

Recharge to the shallow aquifer from canal seepage and infiltration beneath irrigated fields ranges from 54,200 to 104,200 acre-ft/yr (Maurer and others, 1996, fig. 25). Discharge to drains, by evapotranspiration, and by pumping is as much as 95,000 acre-ft/yr. Additionally, about 33,500 acre-ft/yr leaks downward into the intermediate and basalt aquifers in areas where water levels in the shallow aquifer are higher than those in the deeper aquifers. About 21,000 acre-ft/yr leaks upward from the intermediate aquifer where water levels in the deeper aquifers are higher than those in the shallow aquifer (Maurer and others, 1996, p. 25).

Hydraulic Properties

Hydraulic conductivity of the shallow aquifer is highly variable as depicted by the large range in transmissivities from less than 2,000 to 15,000 ft^2/d, with most of the values being less than 2,000 ft^2/d (Glancy, 1986, p. 37). These estimates are based on a simple relation whereby transmissivity (ft^2/d) was approximately equal to 267 times the specific capacity (gal/min/ft of drawdown). The specific capacity data were obtained from Nevada State Engineer's drillers' logs. Assuming that the shallow aquifer averages 40 ft thick and flow to the wells is horizontal, the range in the lateral or horizontal hydraulic conductivity is from less than 50 to 375 ft/d. Lateral hydraulic conductivity of 40 ft/d in the upper 150 ft of sediments northwest of Fallon and near Stillwater was reported by Olmsted and others (1984, p. 38) and Morgan (1982, p. 47).

In the Fallon area, estimates of hydraulic conductivity were based on two types of data. The first was hydraulic conductivities estimated from slug-test data collected from 17 small-diameter wells at the Agricultural Experiment Station south of Fallon, Nev. (Wyn Ross, U.S. Geological Survey, Carson City, Nev., written commun., 1996). For the analyses, the data were assumed to be from an unconfined, incompressible aquifer that is partly penetrated by the wells. Values of hydraulic conductivity ranged from 0.01 to 900 ft/d with a mean of 19 ft/d and a standard deviation of 25 ft/d. However, the arithmetic mean is weighted to values of higher hydraulic conductivity.

The second type of data was from specific capacity obtained from drillers' logs. A search was done for all wells of depth less than 50 ft below land surface within a 5-mi radius from Fallon, Nev. A total of 69 well logs had specific-capacity data that could be used to estimate hydraulic conductivity.

Estimates of hydraulic conductivity from specific capacity data were determined by first estimating transmissivity using the method described by Theis and others (1963) then dividing transmissivity by the perforated interval of the well. The equation used to estimate transmissivity is (modified from eq. 1 of Theis and others to convert units to foot squared per day):

$$T = 15.32(Q/s)(-0.577 - \log_e(r^2 S/4Tt)) \qquad (1)$$

where Q/s is specific capacity of a pumped well, in gallons per minute per foot of drawdown;
r is effective radius of pumped well, in feet;
S is storage coefficient, in cubic feet of water per cubic feet of aquifer;
t is time, in days; and
T is transmissivity, in foot squared per day.

An iterative process, as described by Prudic (1991), was used to solve the equation. An initial estimate of 100 ft^2/d was assumed for T on the right side of equation 1 and a new transmissivity estimated from the equation (T on left side of equation). The new value of

T was then substituted into the right side of the equation. This process was repeated until the difference between transmissivity values on the right and left sides of the equation was less than 0.1 ft^2/d.

The following three assumptions were applied to equation 1 to calculate transmissivity from specific-capacity data. (1) A constant specific yield of 0.15 was assumed as the storage coefficient for all calculations. Specific-yield estimates generally range from 0.10 to 0.25 in unconsolidated sediments such as those found in the study area (Cohen, 1961). Increasing the specific yield from 0.15 to 0.20 results in a slight decrease (about 3 percent) in the estimated transmissivity. (2) The effective radius of the well was taken as equivalent to the actual radius. This assumption may result in too small an estimate of effective radius when the well is highly developed and in unconsolidated materials. Fortunately, uncertainties in the storage coefficients and the effective radius result in generally small differences in the estimate of transmissivity because both are within the log term in equation 1. (3) Well loss was assumed to be minimal. If well loss is not minimal, then the estimates of transmissivity would be too low.

Hydraulic conductivity was estimated for each of the 69 well logs by dividing the calculated transmissivity by the perforated interval of each well. Hydraulic conductivity estimated from the 69 well logs ranged from 6 to 480 ft/d, with a mean of 79 ft/d and a standard deviation of 90 ft/d. The difference between hydraulic conductivity estimated from slug tests to those estimated from specific capacity may be the result of the screening of domestic water wells next to more permeable materials. Another possibility is that the estimated hydraulic conductivities are higher than actual because the aquifer above and below the screened interval contributes water to the well.

The log-normal frequency distribution of hydraulic conductivity estimated from specific-capacity data is shown in figure 4*A*. The distribution of hydraulic conductivity generally is log normal for a variety of aquifer materials (Neuman, 1982). A log-normal distribution suggests that the geometric mean (mean of the log-transformed hydraulic conductivities) may be a better estimate of the average effective hydraulic conductivity for a particular material than the arithmetic mean. Converting estimates of hydraulic conductivity to the logbase 10 results in a geometric mean hydraulic conductivity of 4 ft/d for the 17 estimates from slug tests and 45 ft/d for the 69 estimates from specific-capacity data.

The log-normal frequency distribution of hydraulic conductivity estimated from specific-capacity data suggests that two log-normal distributions can be separated from the one distribution. The two log-normal distributions of hydraulic conductivity may represent the finer sand of interchannel deposits (fig. 4*B*) and coarser sand of channel deposits (fig. 4*C*). The result is a geometric mean hydraulic conductivity for the interchannel deposits of about 22 ft/d and for the channel deposits of 136 ft/d. Both estimates represent only the more permeable deposits within the shallow aquifer. An effective hydraulic conductivity that includes all sediments will likely be less than these values.

Less information is available to estimate hydraulic conductivity in the Stillwater area. Few domestic wells have been drilled in the shallow aquifer in this area because the sediments (mostly clay to fine sand) are either insufficient to yield reasonable quantities of water or because the shallow ground water is of poor quality. A lateral hydraulic conductivity of about 40 ft/d was estimated by Morgan (1982, p. 47) for the sandy sediments. A total of 39 drillers' logs are available for wells drilled within a 5-mi radius of Stillwater. Of these, only four have the necessary information to estimate hydraulic conductivity with techniques similar to those estimated in the Fallon area. In those four cases, hydraulic conductivities ranged from 10 to 134 ft/d. Although these estimates are insufficient to compare with hydraulic conductivities estimated in the Fallon area, the average hydraulic conductivity of the shallow aquifer in the Stillwater area probably is less than that in the Fallon area because of the finer-grained nature of the sediments in this area.

DESCRIPTION OF NUMERICAL MODELS

The shallow aquifer is present throughout much of the Carson Desert (Maurer and others, 1996). However, because the delivery of water to individual farms in the Newlands Project area is complex, a detailed model of flow in the shallow aquifer over the entire project area was not undertaken. Instead, two representative areas were selected to simulate potential effects on water levels and flow in the shallow aquifer caused by changing irrigation practices. The areas chosen were sufficiently large to ascertain the effects of removing small parcels (320 acres) of land from irrigation, without greatly affecting water levels at the model boundaries. The present practice of purchasing water

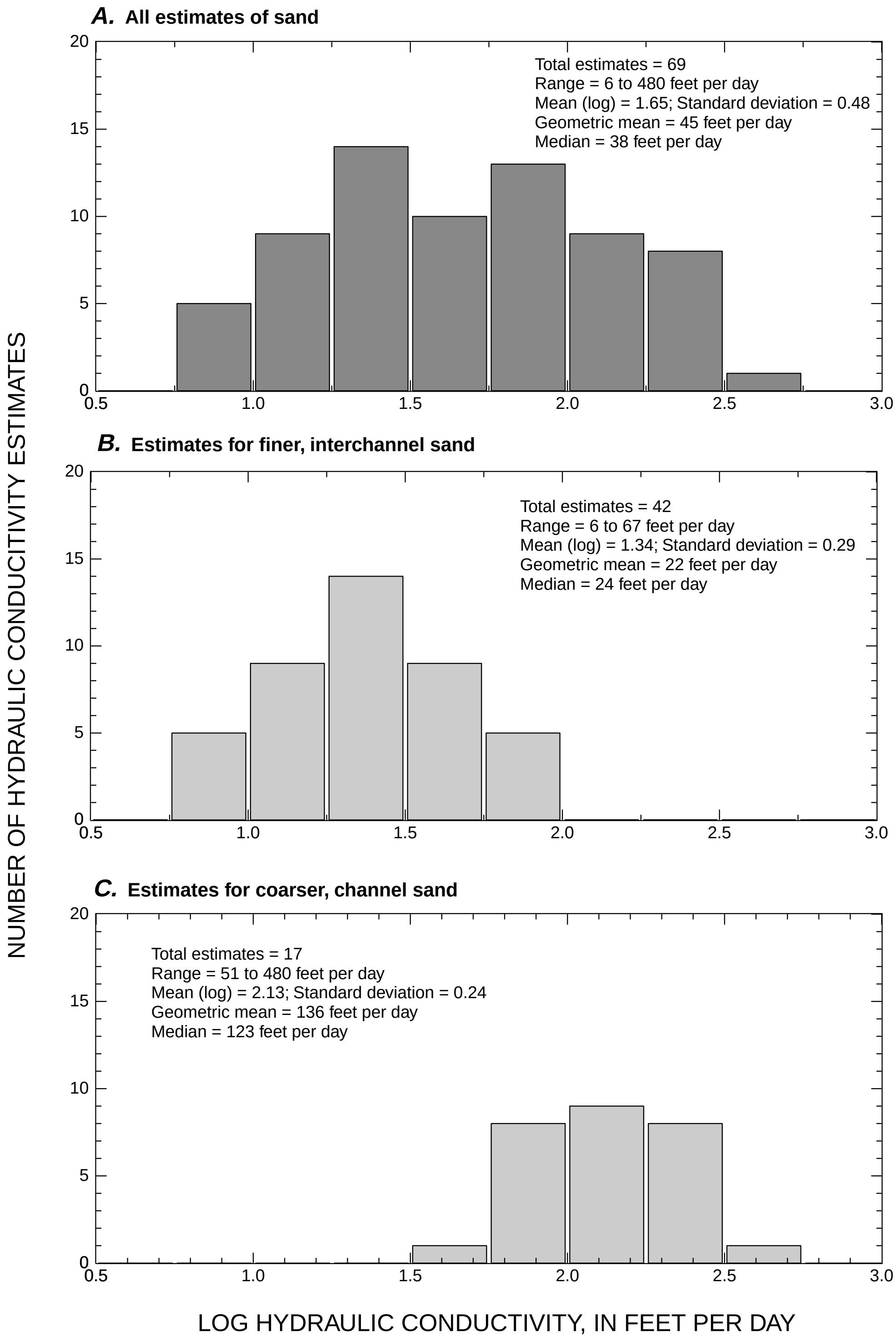


Figure 4. Distribution of hydraulic conductivity estimated from specific-capacity data of wells in shallow aquifer near Fallon, Nevada. Estimates are divided into three groups: (***A***) All estimates of sand; (***B***) Estimates for finer, interchannel sand; and ***(C)*** Estimates for coarser, channel sand.

rights from willing sellers generally results in small parcels of land being removed from irrigation in any given area.

The two areas, each about 9 mi^2 each (5,760 acres), were selected on the basis of having large canals, drains, or both as boundaries along at least two sides. One area just south of Fallon (subsequently referred to as the Fallon area; fig. 2) is characterized by dominantly lateral ground-water flow (Maurer and others, 1996, p. 53) and slightly downward vertical gradients (Glancy, 1986, p. 56). The other area is near Stillwater (subsequently referred to as the Stillwater area; fig. 2), which is characterized by vertical gradients that indicate upward flow through the sedimentary aquifers (Maurer and others, 1996, p. 53). The differences in the two areas provide a basis for comparing changing irrigation practices between areas where shallow flow is dominantly lateral and areas where upward flow from the intermediate aquifer influences flow in the shallow aquifer above.

The major objective of the numerical models is to estimate effects of changes in irrigation practices on water levels, flow, and water quality in the shallow aquifer. The models are not intended to be exact replicates of flow in the shallow aquifer because insufficient data are available to adequately determine the distribution of hydraulic properties of the sediments or the timing and duration of recharge from individual canals and fields. Instead, reasonable approximations of aquifer properties were determined from available data and the models were then used to simulate the general timing and duration of recharge for a typical year. Results for a typical year were then used for comparison with simulations that reduced recharge from canals and fields within the modeled areas.

The shallow aquifer in the Fallon area is separated from the intermediate aquifer by a laterally extensive clay that may be breached in places by former channels of the Carson River (fig. 5*A*). The general direction of ground-water flow is to the southeast (fig. 3) in this area. The shallow aquifer consists mostly of discontinuous layers or lenses of sand, silt, and clay. The most permeable deposits are in the former channels of the Carson River and can occur throughout the shallow aquifer. The dominant recharge of ground water is seepage from unlined canals and from applied irrigation. Ground water is discharged primarily through evapotranspiration (ET) and seepage to drainage ditches (fig. 5*A*).

The shallow aquifer in the Stillwater area, like that in the Fallon area, is separated from the intermediate aquifer by extensive clay units. However, the Stillwater area differs from the Fallon area in that an upward hydraulic gradient from the intermediate aquifer to the shallow aquifer is present (fig. 5*B*). The upward gradient is due, in part, to upwardly moving geothermal water that discharges from depth into the intermediate and shallow aquifers. Much of the geothermal water moves into the intermediate aquifer along fault planes (Morgan, 1982); less flow presumably moves into the shallow aquifer as much of the geothermal water moves laterally through permeable zones in the intermediate aquifer. In addition, sediments in the Stillwater area generally are finer grained and have a greater percentage of silt and clay than those in the Fallon area (Maurer and others, 1996, p. 38) and water generally is more saline in the Stillwater area than in the Fallon area (Maurer and others, 1996, p. 58).

Numerical models were used to estimate changes in water levels and flow in the two selected areas. The remainder of this report describes the models including the general assumptions, features, and results.

Modeling Approach

The USGS modular three-dimensional finite-difference ground-water flow model by McDonald and Harbaugh (1988) and modified by Harbaugh and McDonald (1996a and b) was used to simulate ground-water flow in the Fallon and Stillwater areas. The model uses block-centered, finite-difference approximations to solve the three-dimensional equation of ground-water flow under nonequilibrium conditions in a heterogeneous and anisotropic porous medium with a constant-density fluid and temperature. The equation solved by the program can be written as follows:

$$\partial/\partial x(K_{xx}\partial h/\partial x) + \partial/\partial y(K_{yy}\partial h/\partial y) + \partial/\partial z(K_{zz}\partial h/\partial z) - W = S_s\partial h/\partial t, \qquad (2)$$

where K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivities, in length per unit time (L/t), along the principle x, y, and z coordinate axes,
h is the hydraulic head, in length (L),
W represents all sources and sinks of water as a volumetric flux per unit volume, in units of reciprocal time (t^{-1}),
S_s is specific storage, in units of reciprocal length (L^{-1}), and
t is time.

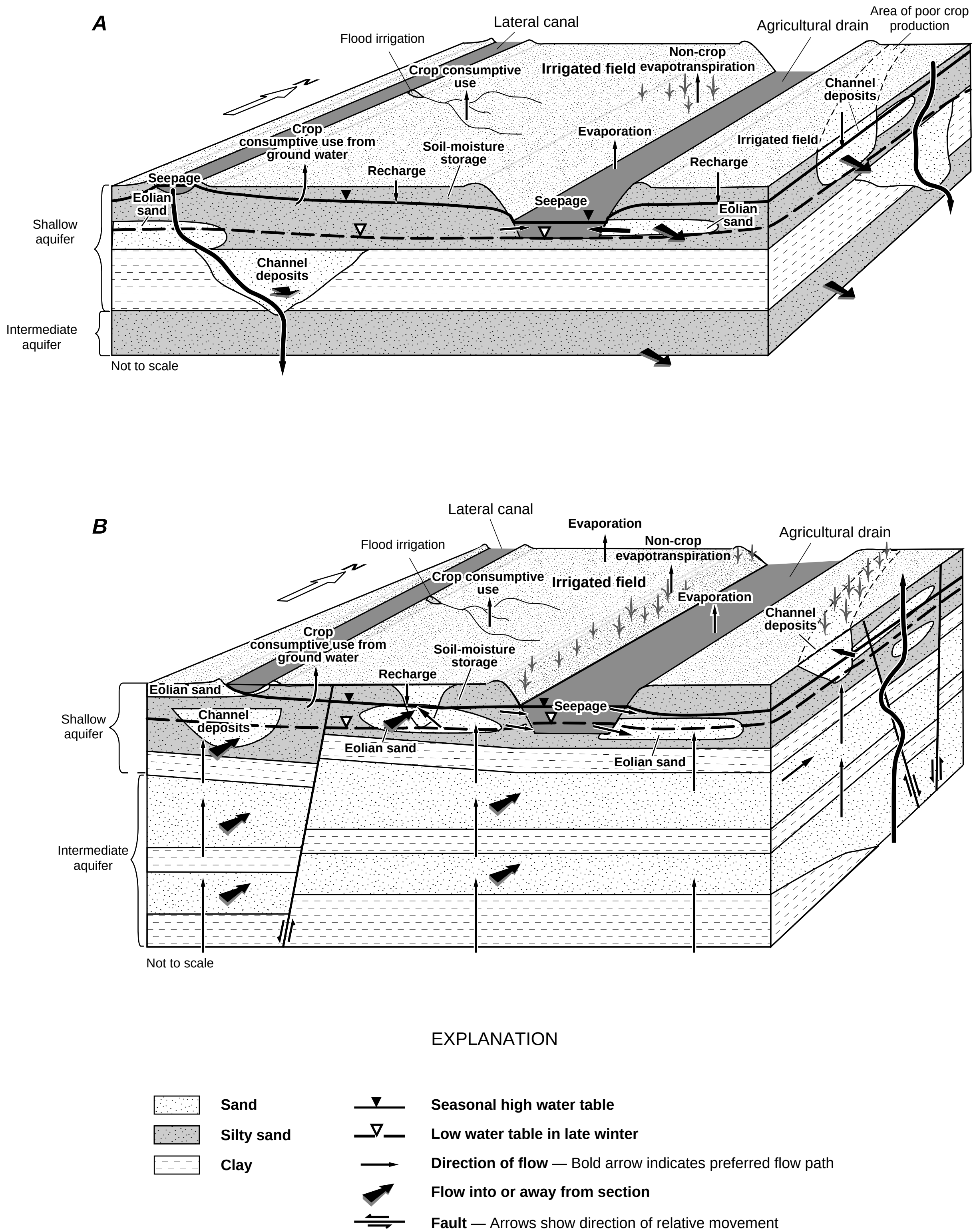


Figure 5. Conceptualizations of ground-water flow in shallow aquifer in irrigated areas near (***A***) Fallon and (***B***) Stillwater, Nevada. Modified from Maurer and others, 1996, figures 28 and 29.

The finite-difference method is used to obtain an approximate solution to equation 2 by replacing the continuous derivatives with a finite set of discrete points in space and time over which differences in water levels are calculated. Surrounding each discrete point or node is a block of dimensions x, y, and z in which the hydraulic properties are assumed to be uniform. An approximation of the solution for water levels at specific points and times is computed by solving a system of linear-algebraic difference equations among all points. The models discussed in this report use the strongly implicit procedure to simultaneously solve these equations.

Calibration Strategy

The strategy for calibration of each model was to approximate water levels and estimates of flow for general conditions while simulating the effect of current irrigation practices. Each model was calibrated to general conditions because records of changes in water levels in the shallow aquifer and on the timing and quantity of water delivered to individual farms were inadequate to duplicate actual water-level variability and water delivery. Therefore, the models were not designed to exactly replicate water levels and flows in the shallow aquifer for any particular time period but rather were calibrated to normal seasonal fluctuations. The general conditions are based on typical irrigation practices during the course of a normal year. The year was divided into six periods to represent changing irrigation practices. The divided year was than repeated for 5 years during calibration because exact initial conditions were not known. The 5-year period was sufficient to attenuate effects caused by errors in the initial conditions. Simulated water levels and flow were repeated for each time period of a year following the second year.

Selection of Stress Periods

Changes in ground-water levels in the Fallon and Stillwater areas are influenced by current irrigation practices. In the shallow aquifer, the water table rises and falls in response to flow in canals and to irrigation (Seiler and Allander, 1993, p. 14). Generally, water levels are highest during the summer and lowest during the winter. Because of the seasonal changes in water levels, an average year was divided into six time or stress periods to simulate changes in recharge and discharge that occur annually in the shallow aquifer. The time periods are (1) Jan. 1-Mar. 31 (recharge and discharge are minimal); (2) Apr. 1-May 31 (recharge from canals and applied irrigation begins as does discharge from ET); (3) June 1-July 15 (recharge from canals and applied irrigation continues and discharge from ET increases); (4) July 16-Aug. 31 (recharge from canals and applied irrigation and discharge from ET continues); (5) Sept. 1-Oct. 31 (recharge from canals and applied irrigation decreases and discharge from ET decreases); and (6) Nov. 1-Dec. 31 (recharge and discharge are minimal).

The total simulated irrigation season is 214 days, which includes 153 days of intense irrigation and 61 days of reduced irrigation (Sept. and Oct.). The total simulated time with no irrigation is 151 days. Each stress period was subdivided into six time steps with the initial time step being dependent on the number of days in an individual stress period. Each subsequent step was increased by 1.5 times the duration of the preceding time step.

Model Grids and Boundaries

Each modeled area was divided into cells that are 330 ft by 330 ft on a side (2.5 acres). The 2.5-acre cell is considered sufficient to represent irrigation practices. The grid for the Fallon model contains 48 rows, 48 columns and all 2,304 cells in the model are active (fig. 6*A*). The grid for the Stillwater model contains 48 rows, 58 columns (fig. 6*B*) with 2,234 active cells out of a total of 2,784 cells in each of two model layers. Only one model layer is used to simulate the vertical dimension of the shallow aquifer. Insufficient information is available regarding aquifer properties and vertical gradients to justify dividing the aquifer into more than one layer. Thus, only lateral flow is simulated in the shallow aquifer. In the modeled areas, a constant depth was assumed for the base of the shallow aquifer and the maximum thickness of sediments is about 50 ft (fig. 7).

Lateral boundaries of each model were selected to coincide with the location of canals, rivers, and drains (fig. 7). These features were simulated as head-dependent flow boundaries. The South Branch of the Carson River intersects the southwest corner of the model grid for the Fallon area (fig. 2). The South Branch was simulated in the model in the same manner as a main canal (fig. 6). The canals and drains only partly penetrate the shallow aquifer, and thus, some

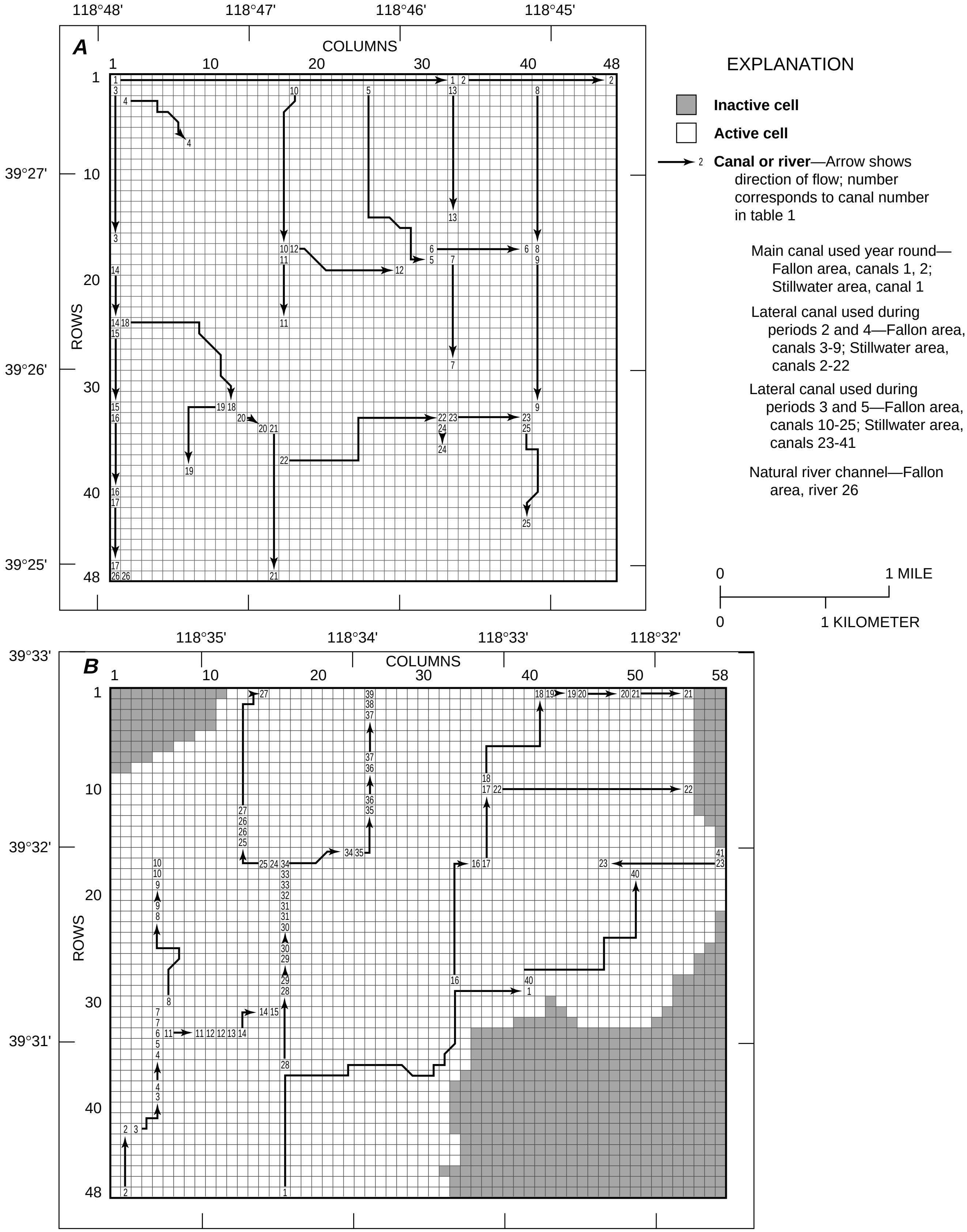


Figure 6. Finite-difference grid and distribution of cells used to simulate canals and rivers as head-dependent boundaries for models of (***A***) Fallon and ***(B)*** Stillwater areas, Nevada.

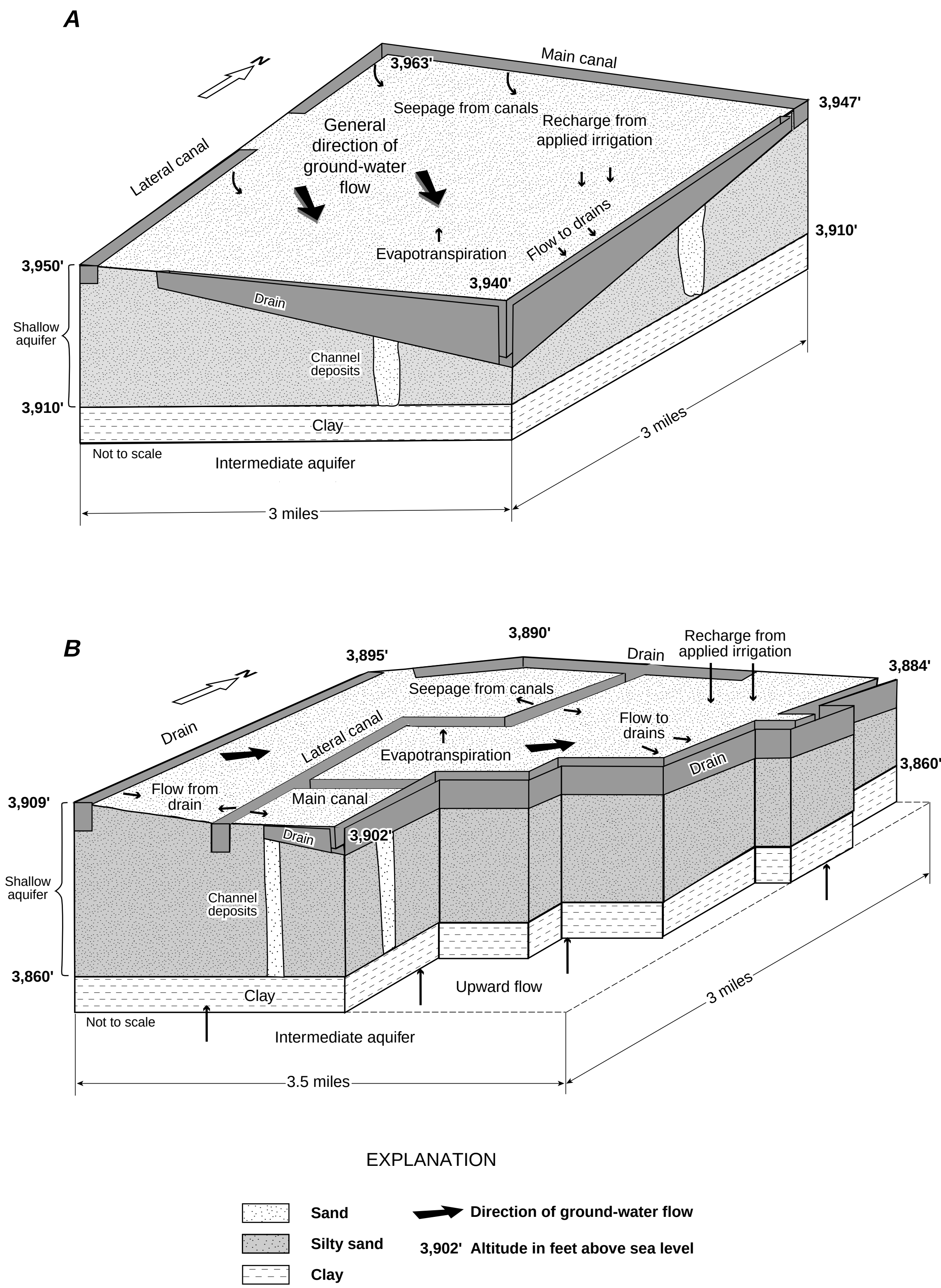


Figure 7. General geometry for models of (***A***) Fallon and ***(B)*** Stillwater areas, Nevada.

flow could move horizontally across the boundaries and beneath the canals and drains. However, a ground-water mound likely develops near canals reducing the chance of lateral flow beneath them. Similarly, drains likely produce a depression in the ground-water table that produces flow to the drain from both sides. Therefore, no horizontal flow was assumed to cross the lateral boundaries. This assumption results in the simulation of greater seepage along canals and more discharge to drains at the lateral boundaries than might actually occur.

Lateral flow into the shallow aquifer in each modeled area can be estimated from Darcy's Law assuming that flow beneath canals and drains is horizontal. In the Fallon area, the general direction of flow is from northwest to southeast (figs. 3 and 7*A*) and, thus, inflow occurs along the north and west sides of the modeled area. Estimated inflow along the north and west sides is about 0.35 ft^3/s (253 acre-ft/yr) assuming an average hydraulic conductivity of about 25 ft/d (about equal to the interchannel deposits) and a hydraulic gradient of 0.001 ft/ft (6 ft/mi). Estimated inflow into the Stillwater area is 0.3 ft^3/s (217 acre-ft/yr). These estimates are probably greater than what may actually flow laterally beneath canals and drains because most of the cross sectional area of the shallow aquifer consists of fine-grained deposits whose hydraulic conductivity is much less than that estimated for the interchannel deposits. Even the larger estimates are a fraction of the estimated seepage from canals and recharge from irrigated areas, and thus, were excluded from the simulations.

One of the most crucial assumptions for both models is the existence of a low permeability clay layer directly beneath the shallow aquifer. The clay layer in the Fallon area is modeled as an impermeable boundary at the base of the shallow aquifer (fig. 7*A*). The clay in the Stillwater area is modeled as a confining unit between two model layers used to represent the shallow and intermediate aquifers (fig. 7*B*). In the Fallon area, the clay layer may have been breached by sand-filled former channels of the Carson River (fig. 5*A*), or in the Stillwater area, the clays may be offset by faults (fig. 5*B*). However, the assumption of a no-flow boundary in the Fallon area is reasonable because the area lies within a region of lateral ground-water flow (Maurer and others, 1996, p. 53) and flow between the shallow and intermediate aquifers is minimal.

Two model layers were used in the Stillwater area to simulate vertical flow into the shallow aquifer from the intermediate aquifer (fig. 7*B*). Upward flow along faults was not simulated in the Stillwater area because their location is not known and flow, where it does occur, is restricted to narrow zones. No flow is assumed beneath the lower model layer in the Still-water area even though upward flow from depth contributes to flow into aquifers that correspond to the intermediate aquifer (Morgan, 1982, fig. 7). Ground-water flow in the intermediate aquifer is generally from south to north (Morgan, 1982, fig. 6). Thus, the southern and northern boundaries of the lower model layer were assigned a specified head, whereas the eastern and western boundaries and the bottom of the aquifer were assumed to be boundaries of no flow. Upward flow from beneath the intermediate aquifer is included in the simulation as lateral flow through the intermediate aquifer.

The water table was simulated as the upper boundary in the modeled areas. Recharge across this boundary is from seepage through canals and drains, and infiltration from applied irrigation. Discharge from this boundary is by ET and ground-water seepage to drains.

Canals and Drains

Canals and drains are not limited to the lateral boundaries because they form an intricate network throughout the modeled areas (figs. 6 and 8). Only the main canals and laterals and the most prominent drains are included in the models. Seepage to and from canals was simulated using the River Package (Harbaugh and McDonald, 1996b, p. 26) because nearly constant heads are maintained in the canals when used. The main canals generally are 30 to 50 ft wide, whereas laterals are 5 to about 20 ft wide. The main canals carry water throughout the irrigation season and generally have greater depth of water compared with the lateral canals. Lateral canals only carry water when it is delivered to groups of farmers. Specified heads for main canals were set on the basis of stage records for 1989—an average year (Willis Hyde, Truckee Carson Irrigation District, Fallon, Nev., written commun., 1998).

Seepage from lateral canals was not simulated for the entire year because the lateral canals carry water approximately 50 percent of the time during the irrigation season (Willis Hyde, Truckee Carson Irrigation District, Fallon, Nev., oral commun., 1997). This seepage was included in model calculations only for selected intervals during the irrigation season to approximate actual usage for delivering water to small groups of farmers. Approximately half of the lateral

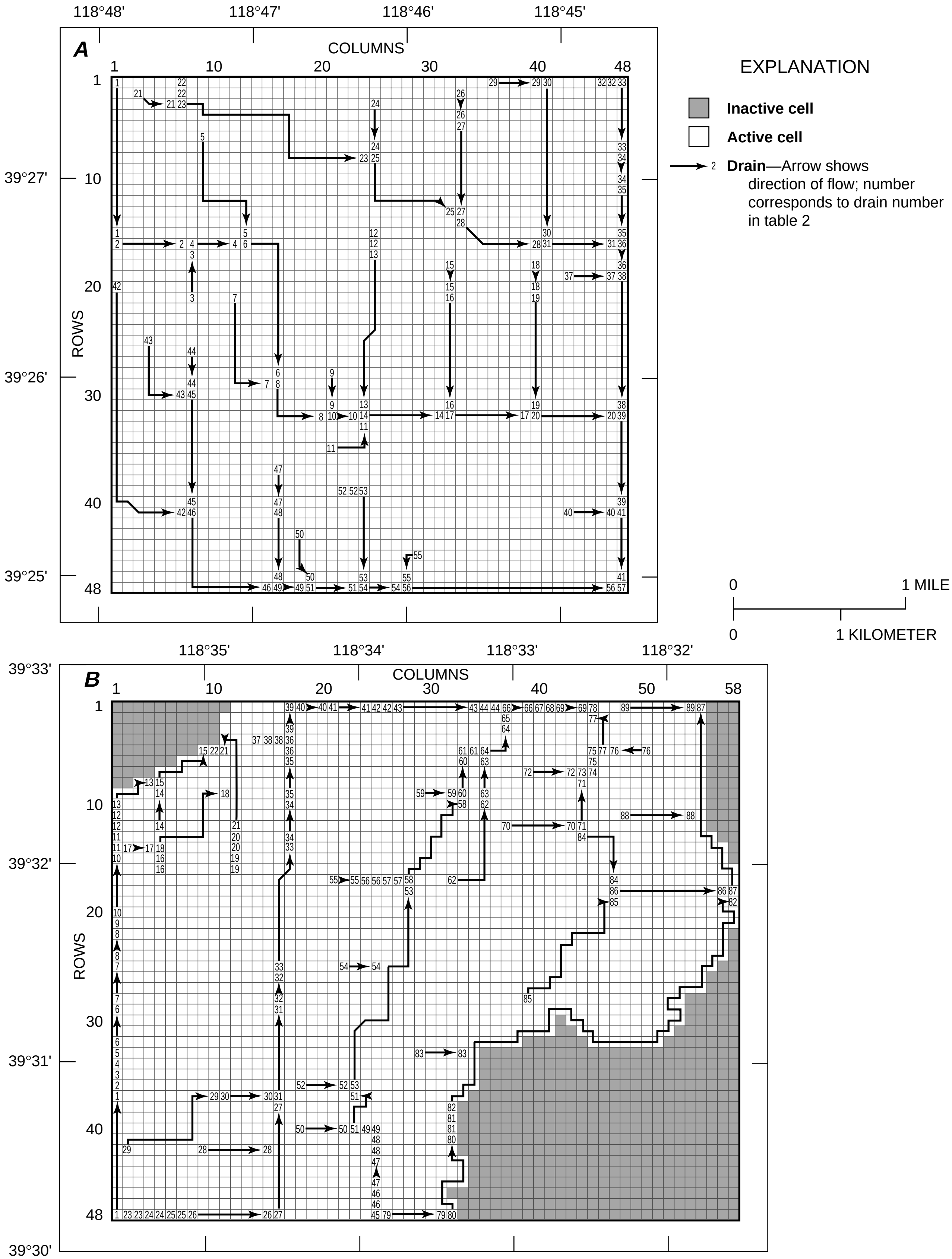


Figure 8. Distribution of cells used to simulate drains as head-dependent boundaries for models of (***A***) Fallon and (***B***) Stillwater areas, Nevada.

canals were simulated for a total of 108 days during the irrigation season, and the other half simulated for a total of 106 days. During winter, the main canals commonly have some flow (although greatly reduced), whereas the laterals generally have no flow. The greatly reduced flow in the main canals was simulated by assigning a water level in the canal equal to the elevation of the canal bed. Lateral canals were assumed to have no water in them during the winter.

Seepage between canals and ground water was simulated with a conductance term that represents the length, width, thickness, and hydraulic conductivity of the sediments lining the canals. A conductance term for model cells containing a canal was estimated from canal length (assumed 330 ft for each cell) and width (varied from 5 to 45 ft), and assuming the sediments lining the canal are 2 ft thick. The vertical hydraulic conductivity of the canal bed was initially assigned a value of 1 ft/d for cells corresponding to interchannel deposits and 10 ft/d for cells corresponding to channel deposits (see fig. 12 for interchannel and channel deposits). Canal width, bed altitude, and water depth were measured in the field at selected locations and values interpolated between measured locations. Table 1 lists water-level and canal-bed elevations, canal width and vertical hydraulic conductivities for canals in the Fallon and Stillwater areas.

Seepage to and from drains was simulated in the modeled areas using the Stream Package (Prudic, 1989). The Stream Package was chosen because the timing of flows in the drains is dependent on seepage from ground water. The Drain Package (Harbaugh and McDonald, 1996b, p. 31) was not used because some drains may at times contribute flow to the shallow aquifer (Maurer and others, 1996, p. 82). Additionally, the Stream Package is designed to sum flows along streams including tributary flows. This made the summing of flows in drains easier in the simulations. Drains in the modeled areas ranged from about 6 ft to 30 ft wide and channel bottoms ranged from about 5 ft to as much as 20 ft below land surface. The drains generally were wider and deeper in the Fallon area. Drains in the Stillwater area generally are less than 20 ft wide and 10 ft deep.

Stage in the drains is computed from simulated flows in the drains using Manning's formula and assuming a rectangular channel. Computation of stage requires estimates of slope, width, and roughness coefficients for each model cell containing a drain. Estimates of width and slope were obtained from field measurements at selected locations along the drains. A roughness coefficient of 0.022 was used for the Fallon area and 0.03 was used for the Stillwater area. The roughness coefficient in the Stillwater area was assigned a higher value because the drains generally have a greater density of vegetation. As with the River Package, seepage between the drains and ground water is simulated through a conductance term. A conductance term was estimated for each cell containing a drain from the estimated width and length of the drain and assuming a hydraulic conductivity the same as that of the shallow aquifer. Table 2 lists drain-bed elevations, widths, conductance terms, and slopes for drains in the Fallon and Stillwater areas.

For drains that began outside the modeled areas, flow was specified at its entry point. For drains that began within the modeled areas, zero flow was specified in the drain where it began. The specified flow for the largest drain entering the Stillwater area was assigned a value of 5 ft^3/s (drain 81, fig. 8). The value is based on flow data from a gage just north of the northeastern edge of the Stillwater area (Willis Hyde, Truckee Carson Irrigation District, Fallon, Nev., written commun., 1997).

Applied Irrigation and Precipitation

Recharge to the water table from applied irrigation and precipitation was simulated using the Recharge Package (Harbaugh and McDonald, 1996b, p. 28). Recharge is simulated as a uniform flux (length per time) over each model cell. This recharge was not simulated over all model cells (fig. 9) because the quantity of water recharging the shallow aquifer from applied irrigation would have been overestimated. Instead, the number of cells with recharge was reduced to equal the percentage of land irrigated in each area. Cells eliminated include those that contained canals next to roads as well as those representing other non-irrigated areas.

The maximum allowable water delivery in the Fallon and Stillwater areas is 3.5 acre-ft/acre/yr (42 in/yr) for years of sufficient supply (Bureau of Reclamation, 1992b, p. 15). Water applied to fields is from small canals that take water from the lateral canals. Water from the small canals is released to fields through flood irrigation. Most of the water released onto the fields replenishes soil moisture and is used by crops; however, some of the water discharges directly into drains and some infiltrates downward to the shallow water table. Of the 42 in/yr (3.5 ft/yr) of water applied to the fields for years with full irrigation

Table 1. Water-level and canal-bed elevations, canal width, and vertical hydraulic conductivities for canals in Fallon and Stillwater modeled areas

Canal number [1]	Water-level Elevation [2] First cell (feet)	Water-level Elevation [2] Last cell (feet)	Canal-bed Elevation [3] First cell (feet)	Canal-bed Elevation [3] Last cell (feet)	Canal width (feet)	Vertical hydraulic conductivity [4] (feet/day)
Fallon modeled area						
1	3,964.6	3,953.5	3,959.1	3,948.0	45	1
2	3,951.5	3,950.1	3,946.0	3,944.6	45	1
3	3,965.9	3,963.2	3,960.9	3,958.2	10	1
4	3,965.7	3,964.9	3,960.7	3,959.9	5	1
5	3,958.0	3,953.8	3,953.0	3,948.8	14	1
6	3,953.6	3,951.8	3,948.6	3,946.8	10	1
7	3,955.0	3,951.8	3,950.0	3,946.8	10	1
8	3,953.0	3,951.0	3,948.0	3,946.0	14	1
9	3,950.9	3,948.2	3,945.9	3,943.2	10	1
10	3,961.0	3,958.9	3,956.0	3,953.9	20	1
11	3,958.7	3,957.6	3,953.7	3,952.6	10	1
12	3,958.0	3,955.8	3,953.0	3,950.8	14	1
13	3,956.0	3,954.0	3,951.0	3,949.0	14	1
14	3,966.0	3,965.0	3,961.0	3,960.0	20	1
15	3,963.0	3,961.6	3,958.0	3,956.6	14	1
16	3,961.4	3,959.5	3,956.4	3,954.5	10	1
17	3,959.2	3,956.5	3,954.2	3,951.5	5	1
18	3,964.8	3,960.0	3,959.8	3,955.0	20	1
19	3,961.6	3,959.8	3,956.6	3,954.8	5	1
20	3,959.0	3,958.6	3,953.0	3,952.6	20	1
21	3,957.4	3,954.0	3,952.4	3,949.0	14	1
22	3,956.6	3,951.8	3,951.6	3,946.8	14	1
23	3,950.4	3,949.0	3,946.4	3,945.0	10	1
24	3,950.5	3,950.3	3,946.5	3,943.9	5	1
25	3,948.9	3,947.0	3,944.9	3,943.9	5	1
26	3,948.0	3,947.7	3,945.0	3,944.7	14	1
Stillwater modeled area						
1	3,904.7	3,897.4	3,898.7	3,891.4	35	1
2	3,908.5	3,907.3	3,903.5	3,902.3	14	1
3	3,907.1	3,906.1	3,902.1	3,901.1	12	10
4	3,905.9	3,905.0	3,900.9	3,900.0	14	10
5 [5]	3,904.8		3,899.8		14	1
6 [5]	3,904.6		3,899.6		14	10
7	3,903.5	3,903.3	3,898.5	3,898.3	12	10
8	3,903.1	3,901.1	3,898.1	3,896.1	12	1
9	3,900.9	3,900.5	3,895.9	3,895.5	10	1
10	3,900.3	3,900.1	3,895.3	3,895.1	10	10
11	3,904.4	3,903.8	3,899.4	3,898.8	12	1

Table 1. Water-level and canal-bed elevations, canal width, and vertical hydraulic conductivities for canals in Fallon and Stillwater modeled areas—Continued

Canal number [1]	Water-level Elevation [2] First cell (feet)	Water-level Elevation [2] Last cell (feet)	Canal-bed Elevation [3] First cell (feet)	Canal-bed Elevation [3] Last cell (feet)	Canal width (feet)	Vertical hydraulic conductivity [4] (feet/day)
12	3,903.6	3,903.4	3,898.6	3,898.4	12	10
13 [5]	3,903.2		3,898.2		12	1
14	3,903.0	3,902.2	3,898.0	3,897.2	12	10
15 [5]	3,902.0		3,897.0		12	1
16	3,897.0	3,895.7	3,892.0	3,890.7	14	1
17	3,892.0	3,891.2	3,887.0	3,886.2	14	1
18	3,891.1	3,889.8	3,886.1	3,884.8	14	10
19	3,889.7	3,889.5	3,884.7	3,884.5	14	1
20	3,889.4	3,889.0	3,884.4	3,884.0	14	10
21	3,888.9	3,888.4	3,883.9	3,883.4	14	1
22	3,891.1	3,889.3	3,886.1	3,884.3	12	1
23	3,892.0	3,890.9	3,886.0	3,884.9	14	1
24 [5]	3,895.0		3,890.0		12	10
25	3,894.8	3,894.0	3,889.8	3,889.0	12	1
26	3,893.8	3,893.6	3,888.8	3,888.6	12	10
27	3,893.4	3,890.8	3,888.4	3,885.8	12	1
28	3,902.8	3,900.0	3,897.8	3,895.0	22	1
29	3,899.6	3,898.8	3,894.6	3,893.8	22	10
30	3,898.4	3,897.6	3,893.4	3,892.6	22	1
31	3,897.2	3,896.8	3,892.2	3,891.8	20	1
32 [5]	3,896.4		3,891.4		18	1
33	3,896.0	3,895.6	3,891.0	3,890.6	16	1
34	3,895.3	3,894.0	3,890.3	3,889.0	14	1
35	3,893.8	3,892.8	3,888.8	3,887.8	12	1
36	3,892.6	3,892.3	3,887.6	3,887.3	12	10
37	3,892.2	3,891.8	3,887.2	3,886.8	12	1
38 [5]	3,891.7		3,886.7		12	10
39 [5]	3,891.6		3,886.6		12	1
40	3,896.4	3,891.0	3,891.4	3,886.0	12	1
41 [5]	3,890.2		3,885.2		14	1

[1] Canal numbers correspond to numbers shown in figure 6. Canal 26 in Fallon modeled area is a river.

[2] Water-level elevations of canal is the elevation of water in canal in feet above mean sea level for period when water is in canal. During winter months (stress periods 1 and 6), water-level elevations in main canals are set equal to canal-bed elevation, as usually there is small quantity of water in canal; other canals are not simulated.

[3] Canal-bed elevations are bottom of canal bed in feet above sea level. Canal beds were assumed to have a uniform thickness of 2 feet.

[4] A uniform vertical hydraulic conductivity of 1 foot per day used in model of Fallon area.

[5] Only one cell assigned to canal number.

Table 2. Drain-bed elevation, drain width, drain-bed conductance, and drain-bed slope values for Fallon and Stillwater modeled areas

Drain number [1]	Drain-bed Elevation [2] First cell (feet)	Drain-bed Elevation [2] Last cell (feet)	Drain width (feet)	Drain-bed conductance [3] (feet squared per day)	Drain-bed slope (foot per foot)
Fallon modeled area					
1	3,956.0	3,953.2	15	22,464	0.0006
2	3,953.0	3,951.8	20	29,981	.0005
3	3,953.0	3,952.0	10	15,034	.0005
4	3,951.6	3,950.8	20	29,981	.0005
5	3,953.6	3,950.8	15	22,464	.0007
6	3,950.6	3,946.0	20	29,981	.001
7	3,948.2	3,945.8	15	22,464	.0006
8	3,945.7	3,943.8	20	29,981	.0008
9	3,944.4	3,943.8	10	15,034	.0005
10	3,943.6	3,943.2	20	29,981	.0005
11	3,944.2	3,943.2	10	15,034	.0006
12	3,947.7	3,947.3	10	15,034	.0008
13	3,947.0	3,943.2	15	22,464	.0008
14	3,943.0	3,941.3	20	29,981	.0007
15	3,945.7	3,945.0	10	15,034	.001
16	3,944.7	3,941.3	15	22,464	.001
17	3,941.0	3,936.8	20	29,981	.002
18	3,944.6	3,943.4	10	15,034	.002
19	3,942.8	3,936.8	15	22,464	.002
20	3,936.2	3,931.5	20	29,981	.002
21	3,958.5	3,957.6	10	15,034	.0008
22	3,957.7	3,957.5	15	22,464	.0008
23	3,957.3	3,951.2	15	22,464	.0009
24	3,952.0	3,951.2	10	15,034	.0006
25	3,951.0	3,948.2	15	22,464	.0008
26	3,951.6	3,951.0	10	15,034	.0009
27	3,950.7	3,948.3	15	22,464	.0009
28	3,948.0	3,942.7	15	22,464	.002
29	3,949.0	3,947.0	10	15,034	.001
30	3,946.5	3,942.3	15	22,464	.0009
31	3,942.0	3,936.0	20	22,464	.003
32	3,942.0	3,941.5	10	15,034	.001
33	3,941.0	3,938.5	15	22,464	.001
34	3,938.0	3,937.0	20	29,981	.001
35	3,936.7	3,935.7	25	37,498	.001
36	3,935.3	3,934.6	30	45,014	.001
37	3,944.0	3,940.0	10	15,034	.003
38	3,934.4	3,931.3	30	45,014	.0009
39	3,931.0	3,925.6	30	45,014	.002
40	3,938.0	3,934.0	10	15,034	.003

Table 2. Drain-bed elevation, drain width, drain-bed conductance, and drain-bed slope values for Fallon and Stillwater modeled areas—Continued

Drain number [1]	Drain-bed Elevation [2] First cell (feet)	Drain-bed Elevation [2] Last cell (feet)	Drain width (feet)	Drain-bed conductance [3] (feet squared per day)	Drain-bed slope (foot per foot)
41	3,925.0	3,920.6	30	45,014	0.002
42	3,955.0	3,950.1	10	15,034	.0006
43	3,955.0	3,953.2	10	15,034	.0007
44	3,953.8	3,953.2	10	15,034	.0005
45	3,953.0	3,950.3	15	22,464	.0008
46	3,950.0	3,945.3	15	22,464	.001
47	3,948.3	3,947.4	10	15,034	.0009
48	3,947.1	3,945.3	15	22,464	.0009
49	3,945.0	3,944.5	20	29,981	.0007
50	3,947.0	3,945.0	10	15,034	.001
51	3,944.2	3,942.5	20	29,981	.001
52	3,945.5	3,945.2	10	15,034	.0006
53	3,945.0	3,942.5	15	22,464	.001
54	3,942.0	3,941.0	20	29,981	.001
55	3,943.0	3,941.5	10	15,034	.0007
56	3,940.0	3,921.0	20	29,981	.003
57 [4]	3,920.0		30	45,014	.003
Stillwater modeled area					
1	3,901.1	3,897.5	16	2,640	.001
2 [4]	3,897.2		14	2,310	.001
3 [4]	3,896.8		12	1,980	.001
4 [4]	3,896.5		10	1,650	.001
5 [4]	3,896.2		7	1,155	.001
6	3,893.1	3,892.8	14	2,310	.0003
7	3,892.7	3,892.4	15	2,475	.0003
8	3,892.3	3,892.1	16	2,640	.0003
9 [4]	3,892.0		16	26,400	.0003
10	3,891.9	3,891.2	17	2,805	.0003
11	3,891.0	3,890.7	18	2,970	.0008
12	3,890.4	3,890.1	19	3,135	.0008
13	3,889.9	3,885.0	20	3,300	.0008
14	3,888.0	3,888.0	6	990	.0003
15	3,884.0	3,883.0	20	3,300	.0008
16	3,893.0	3,891.0	6	990	.0003
17	3,893.0	3,891.0	6	990	.0003
18	3,890.0	3,887.0	6	990	.0003
19	3,889.0	3,889.0	6	990	.0003
20	3,888.0	3,888.0	6	9,900	.0003
21	3,887.0	3,883.0	6	990	.0003
22 [4]	3,882.0		20	3,300	.0008
23	3,904.0	3,904.0	11	1,815	.001
24	3,904.0	3,903.0	10	1,650	.001
25	3,904.0	3,904.0	9	1,485	.001

Table 2. Drain-bed elevation, drain width, drain-bed conductance, and drain-bed slope values for Fallon and Stillwater modeled areas—Continued

Drain number [1]	Drain-bed Elevation [2] First cell (feet)	Drain-bed Elevation [2] Last cell (feet)	Drain width (feet)	Drain-bed conductance [3] (feet squared per day)	Drain-bed slope (foot per foot)
26	3,903.0	3,903.0	8	1,320	0.001
27	3,903.0	3,900.0	8	1,320	.0004
28	3,903.0	3,902.0	6	990	.0003
29	3,905.0	3,901.0	6	9,900	.0003
30	3,901.0	3,901.0	6	990	.0003
31	3,899.0	3,896.0	8	1,320	.0004
32	3,895.0	3,894.0	8	13,200	.0004
33	3,894.0	3,887.0	8	1,320	.0004
34	3,887.0	3,887.0	8	13,200	.0004
35	3,887.0	3,887.0	8	1,320	.0004
36	3,887.0	3,887.0	8	13,200	.0004
37 [4]	3,887.0		6	990	.0003
38	3,887.0	3,887.0	6	9,900	.0003
39	3,887.0	3,887.0	8	1,320	.0004
40	3,885.0	3,885.0	10	1,650	.0004
41	3,886.0	3,886.0	10	16,500	.0004
42	3,886.0	3,886.0	10	1,650	.0004
43	3,885.0	3,881.0	12	1,980	.0004
44	3,881.0	3,880.0	14	2,310	.0004
45 [4]	3,901.0		8	1,320	.0006
46	3,901.0	3,901.0	8	13,200	.0006
47	3,900.0	3,900.0	8	1,320	.0006
48	3,900.0	3,900.0	8	13,200	.0006
49	3,900.0	3,900.0	8	1,320	.0006
50	3,901.0	3,901.0	6	990	.0003
51	3,899.0	3,899.0	10	1,650	.0006
52	3,899.0	3,898.0	6	990	.0003
53	3,898.0	3,889.0	12	1,980	.0006
54	3,896.0	3,896.0	6	990	.0003
55	3,890.0	3,890.0	6	990	.0003
56	3,890.0	3,889.5	6	9,900	.0003
57	3,891.0	3,891.0	6	990	.0003
58	3,889.0	3,886.0	12	1,980	.0006
59	3,888.0	3,887.0	6	9,900	.0003
60	3,886.0	3,885.0	12	19,800	.0006
61	3,885.0	3,884.0	12	1,980	.0006
62	3,895.0	3,888.0	6	990	.0003
63	3,888.0	3,887.0	6	9,900	.0003
64	3,884.0	3,882.0	12	19,800	.0006
65 [4]	3,882.0		12	1,980	.0006

Table 2. Drain-bed elevation, drain width, drain-bed conductance, and drain-bed slope values for Fallon and Stillwater modeled areas—Continued

Drain number [1]	Drain-bed Elevation [2] First cell (feet)	Drain-bed Elevation [2] Last cell (feet)	Drain width (feet)	Drain-bed conductance [3] (feet squared per day)	Drain-bed slope (foot per foot)
66	3,881.0	3,881.0	14	2,310	0.0004
67 [4]	3,881.0		14	23,100	.0004
68 [4]	3,879.0		16	26,400	.0004
69	3,879.0	3,878.0	16	2,640	.0004
70	3,888.0	3,886.0	6	990	.0003
71	3,887.0	3,884.0	8	1,320	.0006
72	3,886.0	3,885.0	6	9,900	.0006
73 [4]	3,884.0		10	1,650	.0006
74 [4]	3,882.0		10	16,500	.0006
75	3,882.0	3,882.0	10	1,650	.0006
76	3,882.0	3,881.0	6	990	.0003
77	3,881.0	3,880.0	12	19,800	.0006
78 [4]	3,878.0		16	26,400	.0004
79	3,901.0	3,900.0	4	660	.0003
80	3,894.0	3,893.0	20	3,300	.0004
81	3,893.0	3,893.0	20	33,000	.0004
82	3,893.0	3,883.0	20	3,300	.0004
83	3,899.0	3,896.0	6	990	.0003
84	3,888.0	3,886.0	6	990	.0003
85	3,895.0	3,887.0	6	990	.0003
86	3,886.0	3,884.0	8	1,320	.0006
87	3,883.0	3,876.0	20	3,300	.0004
88	3,885.0	3,884.0	6	990	.0003
89	3,882.0	3,880.0	8	1,320	.0006

[1] Drain numbers correspond to numbers shown in figure 8.

[2] Drain-bed elevations are top of drain bed in feet above land surface.

[3] Drain-bed conductance is vertical hydraulic conductivity multiplied by area of drain (width times length) and divided by thickness of bed (assumed 2 feet).

[4] Only one cell assigned to drain number.

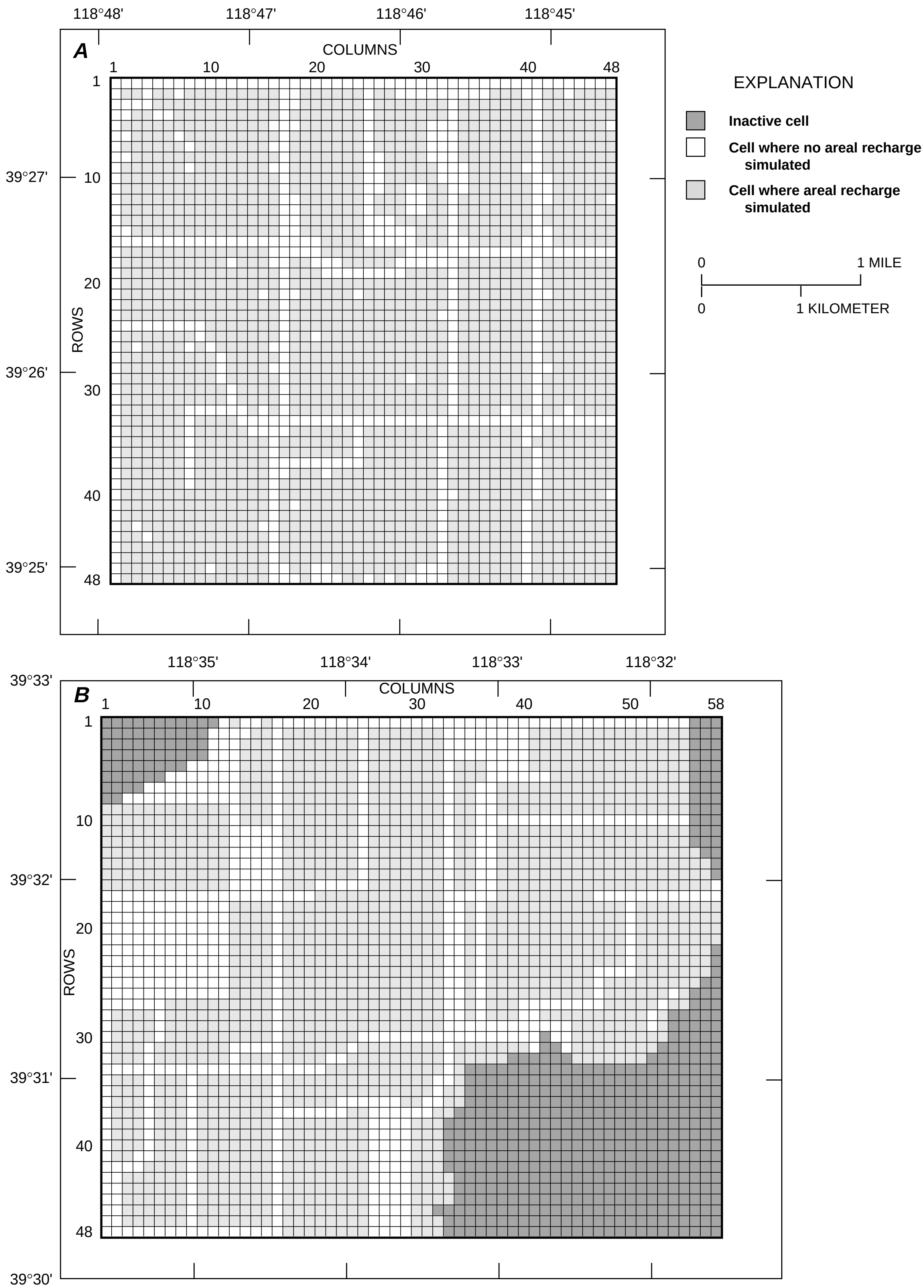


Figure 9. Distribution of cells used to simulate recharge from applied irrigation and precipitation for models of (***A***) Fallon and (***B***) Stillwater areas, Nevada.

entitlement, about two thirds (28 in/yr) is consumed by crops (Chambers and Guitjens, 1995). This difference implies that about 14 in/yr could percolate downward and recharge the shallow aquifer.

Much of the ground-water recharge from applied irrigation occurs during the growing season from April through October. Evapotranspiration (see next section) from agricultural crops consumes most of the applied irrigation. ET for each stress period was estimated on the basis of crop type and monthly potential ET. Recharge for each stress period was estimated by subtracting ET consumed by crops from typical estimates of applied irrigation for each stress period (Pennington, 1980). The distribution of recharge rates for each stress period is listed in table 3 and shown in figure 10*A*. The distribution results in most of the recharge occurring during the period of irrigation.

Infiltration of precipitation is a small percentage of the total ground-water recharge but supplies much of the recharge during the winter when fields are not being irrigated (table 3; fig. 10*A*). Infiltration of precipitation may be enhanced in areas where moisture content of the sediments is high, such as the sediments beneath irrigated areas (Olmsted, 1985, p. 15). Annual recharge from precipitation was estimated as 1.75 in/yr. This rate is based on the assumption that the fraction of ground-water recharge from irrigation activities and from precipitation on irrigated fields is equivalent (one third). Recharge from precipitation was distributed among the stress periods on the basis of monthly average precipitation (Owenby and Ezell, 1992). Recharge from precipitation is greatest from April through May and least during July and August (table 3; fig. 10*A*).

Evapotranspiration

Evapotranspiration from ground water was simulated using the ET Package (Harbaugh and McDonald, 1996b, p. 33). The package is used to simulate discharge of ground water by ET only and does not include ET from soil water above the water table. In the model simulations, ET from ground water is calculated whenever the water table is within a given range of elevation. The quantity of ground-water discharge from ET is calculated by multiplying a rate with the area of the model cell. The rate decreases linearly from a maximum at a specified elevation (land surface) to zero when the water table is below a specified depth (10 ft below land surface). This depth is based on work by Nichols (1994) in which ground-water discharge from ET by phreatophytes is small below a depth of 10 ft.

Table 3. Estimated recharge rates from precipitation and applied irrigation and maximum evapotranspiration rates for selected time periods for models of Fallon and Stillwater areas, Nevada

[Values in inch per day, rounded to nearest 0.001 inch]

Stress period	Time period	Average precipitation rate [1]	Recharge rate from precipitation [2]	Average rate of applied irrigation [3]	Recharge rate of applied irrigation [4]	Total recharge rate [5]	Maximum rate of evapotranspiration [6]
1	Jan. 1 - Mar. 31	0.016	0.005	0.000	0.000	0.005	0.041
2	Apr. 1 - May 31	.020	.007	.207	.069	.076	.257
3	June 1 - July 15	.015	.005	.280	.093	.098	.309
4	July 16 - Aug. 31	.009	.003	.268	.089	.092	.211
5	Sept. 1 - Oct. 31	.013	.004	.069	.023	.027	.126
6	Nov. 1 - Dec. 31	.013	.004	.000	.000	.004	.051

[1] Average precipitation rates for each stress period determined from Owenby and Ezell (1992) for 1961-90. Average annual precipitation is 5.3 inches.

[2] Assumes one-third of average precipitation rate recharges shallow aquifer in areas of irrigation.

[3] Assumes 90 percent of annual rate of 42 inches per year is applied during stress periods 2, 3, and 4, and 10 percent is applied during stress period 5. Percentages based on applications reported by Guitjens and Mahannah (1974).

[4] Assumes one-third of applied irrigation recharges shallow aquifer. Fraction is based on estimates from Chambers and Guitjens (1995).

[5] Total recharge rate is sum of recharge from precipitation and applied irrigation.

[6] Maximum evapotranspiration rates are based on estimated potential evapotranspiration from class A pan evaporation rates (Wilcox, 1978; Pennington, 1980).

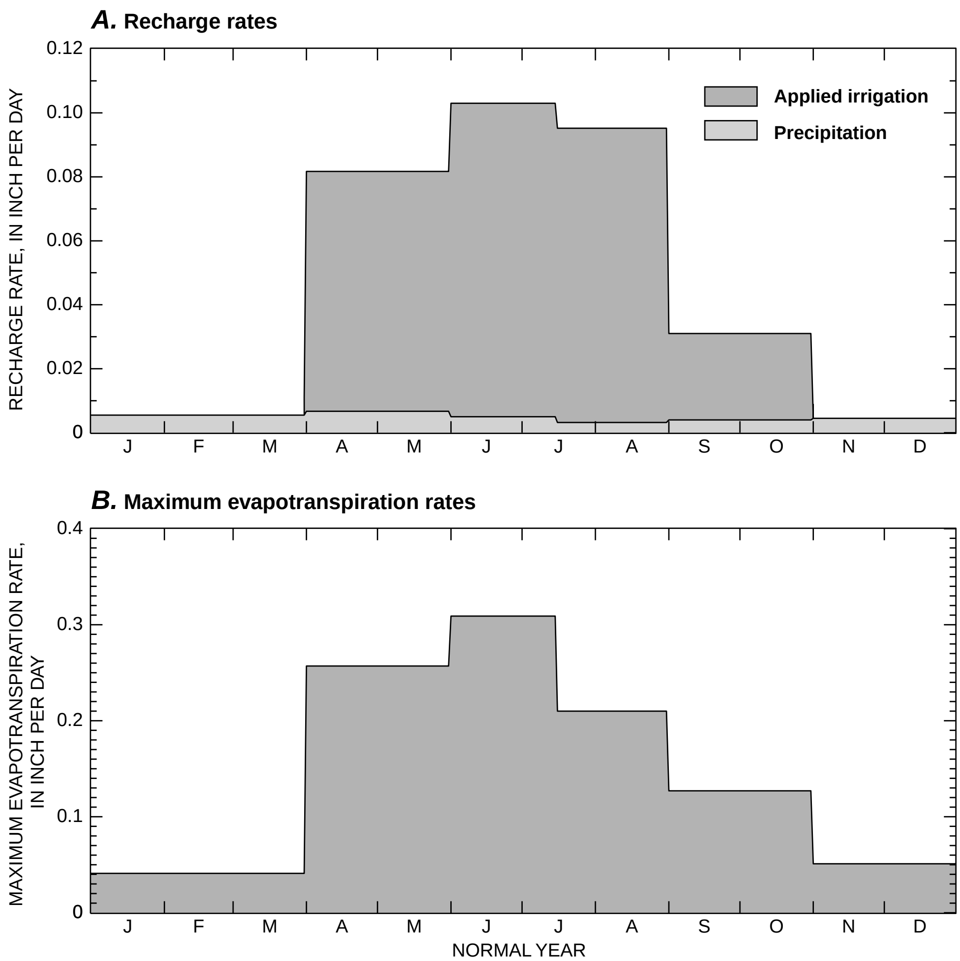


Figure 10. Recharge rates beneath irrigated fields and maximum evapotranspiration rates for selected time periods used in models of ground-water flow in (***A***) Fallon and (***B***) Stillwater areas, Nevada.

Evapotranspiration from agricultural crops was not simulated explicitly in the model as crop consumption losses were subtracted from the applied irrigation and precipitation to obtain an estimate of recharge. Much of the ground-water discharge from ET simulated in the model is from phreatophytes that exist along the margins of the fields and in non-irrigated areas. However, some ground water probably is consumed by deeply-rooted crops such as alfalfa.

The maximum ET rate varies seasonally and is dependent on the potential ET rate, which is highest during summer and lowest during winter. A maximum annual rate for ET was estimated as 54 in/yr, which is an average rate of evaporation from open-water surfaces in the Fallon area (Geraghty and others, 1973). This rate compares well to estimates of 52.1, 57.4, 55.6, 59.4, and 57.1 in/yr using the Blaney-Criddle, Radiation, Penman, Corrected Penman, and Pan Evaporation [Food and Agricultural Organization (FAO) modified] methods, respectively, for well-watered plants at Fallon (Pennington, 1980, p. 115). Potential ET values for Fallon using measured temperature and calculated ratio of total radiation to vertical radiation range from 49.6 to 61.4 in/yr (Shevenell, 1996).

The maximum ET rate of 54 in/yr was distributed over the six stress periods on the basis of monthly averaged potential ET (Wilcox, 1978; Pennington, 1980). Maximum ET rate for each simulation time period during a typical year is listed in table 3 and shown in figure 10*B*. The highest rate was estimated for the period June 1 through July 15 and the lowest rate was estimated for the period Jan. 1 through Mar. 31.

Wells

Withdrawals from wells were simulated using the Well Package (Harbaugh and McDonald, 1996b, p. 29). A flow rate (volume per time) is specified for each well and assigned to a model cell. Drillers' logs were used to determine the location, depth, and number of wells used for domestic, municipal, industrial, agricultural, or monitoring purposes. Only wells with a depth of less than 50 ft below land surface were used in the modeled areas. All wells drilled in the shallow aquifer are either domestic or monitoring wells. Only domestic wells were assigned a withdrawal rate. A total of 189 domestic wells were identified in the Fallon area and 14 in the Stillwater area (fig. 11). The wells were assigned to model cells using the township, range, and section location provided on the drillers' log. Often, the location is known to within a quarter-quarter section (40 acres) and a cell corresponding to that location was selected. When more than one well was in a quarter-quarter section, the wells were distributed evenly among the corresponding model cells. The distribution of wells in each model area is shown in figure 11.

The average flow rate of water pumped for a domestic well was estimated to be 1,200 gal/d. This flow rate is based on four people per household with 300 gal/d per-capita use. This estimate is slightly more than the 270 gal/d per-capita use for 1980 (Glancy, 1986, table 7). However, only 300 gal/d was assigned as the withdrawal rate because much of the pumped water returns to the aquifer through septic systems. About 75 percent of the pumped water was assumed to enter the septic system and recharge the shallow aquifer. Reducing the pumping rate to account for recharge from septic systems was done because withdrawal from wells and recharge from septic systems typically occurs within the same model cell (2.5 acres).

Initial Conditions

An initial water level must be specified for transient simulations. During model calibration, an initial water level was assigned to each cell assuming the water table was 10 ft below land surface. Initial water levels were assigned to the intermediate aquifer in the Stillwater area assuming a uniform gradient between the south and north boundaries. Because the actual water-level distribution was unknown for the beginning of the simulations, the six stress periods used to represent changes in recharge and discharge during a normal year were repeated until simulated water levels and water budgets during a year matched those from the previous year. Water levels and water budgets during the third year usually matched those of the second year. As a precaution, all simulations were extended for 5 years or a total of 30 stress periods. Water levels simulated from the third through fifth years represent a dynamic equilibrium with recharge and discharge and aquifer properties used in the modeled areas because the yearly cycles are repeatable with no net change in storage (Anderson and Woessner, 1992, p. 201).

Following model calibration, the simulated water levels at the end of the last stress period (5 years) were assigned as initial water levels for simulations that were used to test sensitivity of hydraulic properties and to analyze changes caused by reducing irrigation water.

Hydraulic Properties

The shallow aquifer consists of lenses or layers of sand deposited by rivers or along the edges of lakes (beach deposits) mixed with finer-grained silt and clay deposited in lakes or depressions. For the modeled areas, the shallow aquifer was divided into two types of deposits: fine sand deposited in interchannel areas along the margins of lakes or in slower moving water and coarse sand deposited in former stream channels. Although the two deposits are present over discrete depth intervals in the shallow aquifer, insufficient data are available to describe their distribution. Instead, the assumptions of both models are that the two deposits are distributed on the basis of their distribution on the surface (Maurer and others, 1996, pl. 3) and that each deposit extends downward to the bottom of the shallow aquifer. The distribution of the two sand deposits in each modeled area is shown in figure 12. The effect of assuming laterally and vertically continuous units is to produce zones of more rapid ground-water flow where channel deposits are present at the land surface.

Properties required for modeling ground-water flow in the shallow aquifer are horizontal hydraulic conductivity and specific yield. In the Stillwater area, additional properties were needed for the intermediate aquifer, which include horizontal hydraulic conductivity, specific storage, and vertical hydraulic conductivity of the fine-grained deposits between the shallow and intermediate aquifers.

In the Fallon area, horizontal hydraulic conductivity of the interchannel deposits initially was assumed to be 10 ft/d or about half the geometric mean from

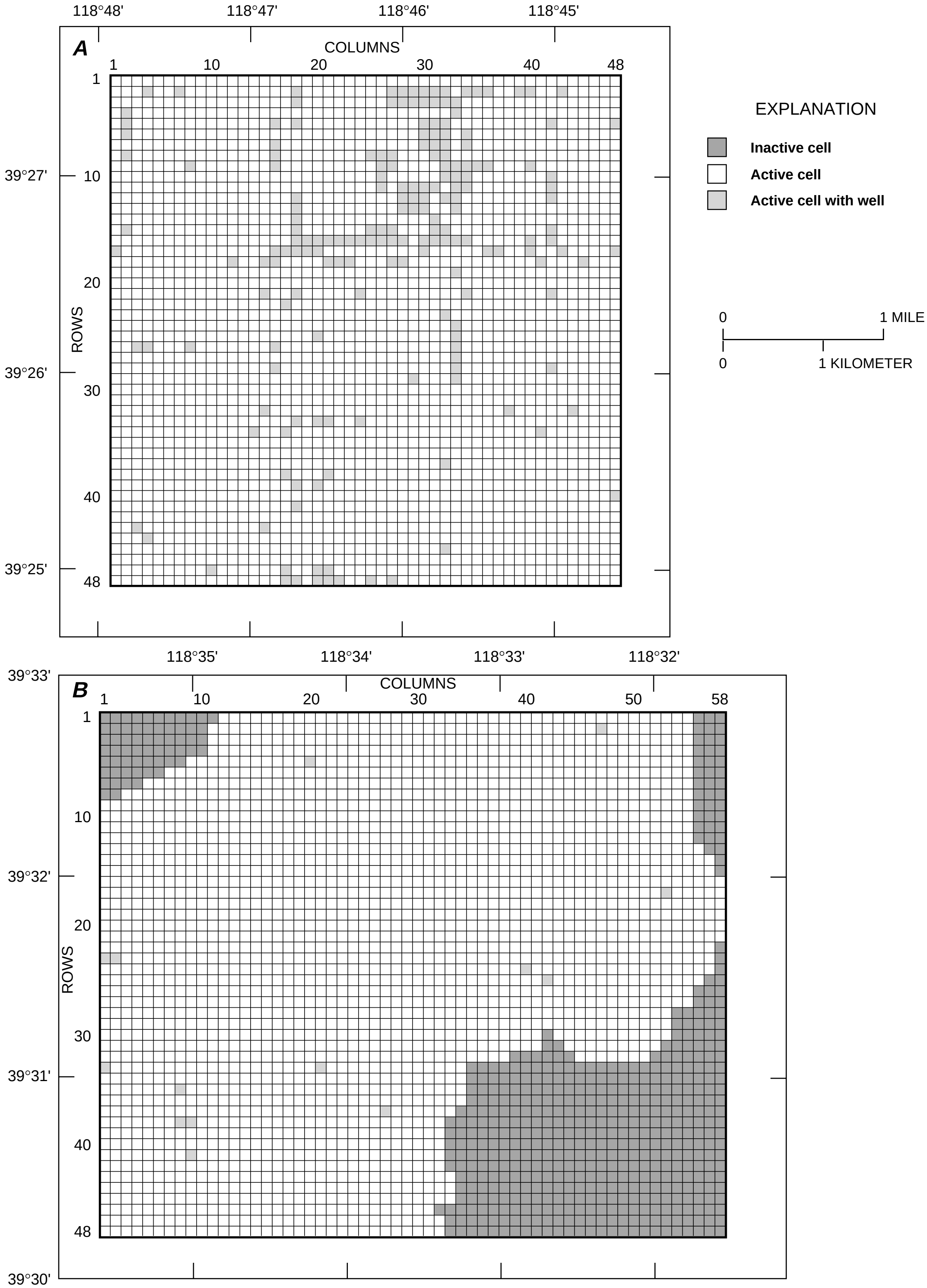


Figure 11. Distribution of cells used to simulate withdrawals from wells for models of (***A***) Fallon and (***B***) Stillwater areas, Nevada.

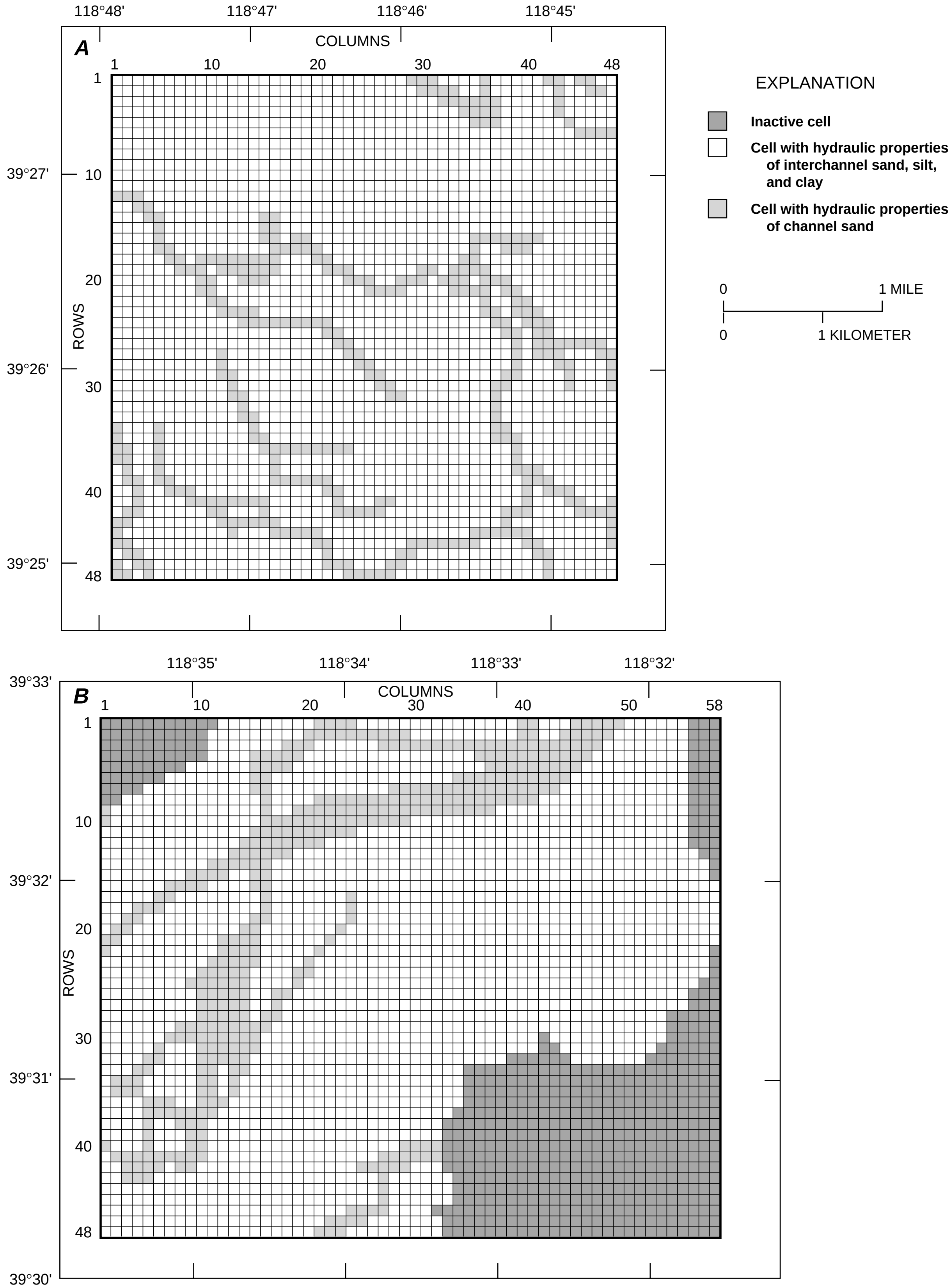


Figure 12. Distribution of surface channel and interchannel deposits used to assign hydraulic properties of shallow aquifer for models of (***A***) Fallon and (***B)*** Stillwater areas, Nevada

specific-capacity data (fig. 4). The value was reduced because the shallow aquifer does not consist entirely of the more permeable deposits reflected in the specific-capacity data. Alternatively, the thickness of the shallow aquifer could have been reduced to include only the thickness of the more permeable deposits.

Hydraulic conductivity of the channel deposits in the Fallon area initially was assumed to be 100 ft/d and was reduced by about 25 percent from the geometric mean from specific-capacity data (fig. 4). Hydraulic conductivity was changed during calibration such that simulated drain flows were less than those measured. Specific yield of the interchannel deposits initially was assumed to be 0.15; whereas, the specific yield of the channel deposits was assumed to be 0.20. These values are slightly less than the specific yields determined for fine and coarse sand (Johnson, 1967, p. D1).

The horizontal hydraulic conductivity of the shallow aquifer in the Stillwater area for fine sand was assumed to be 5 ft/d and for coarse sand was assumed to be 50 ft/d. These values are half of those in the Fallon area and reflect a greater percentage of fine-grained deposits in the Stillwater area. Although no estimate of the percentage of fine-grained deposits was made in either area, the greater percentage of clay found in the few available well logs suggests that the percentage of fine and coarse sands in the Stillwater area is less than that in the Fallon area. Assigned specific-yield values were 0.20 for the fine sand and 0.26 for the coarse sand.

A transmissivity of 2,000 ft^2/d was assigned to the intermediate aquifer (model layer 2) in the Stillwater area. This transmissivity is based on a hydraulic conductivity of 40 ft/d and a sand thickness of 50 ft for primary aquifer 2 of Morgan (1982, p. 47 and table 5). Primary aquifer 2 corresponds to the upper part of the intermediate aquifer. The intermediate aquifer generally has transmissivities of less than 2,000 ft^2/d (Glancy, 1986, p. 51 and 54). A specific storage of 1.0×10^{-6} per foot of aquifer thickness (Lohman, 1972, p. 8) was used to calculate a storage coefficient of 5.0×10^{-5} assuming a thickness of 50 ft.

Vertical flow between the shallow and intermediate aquifers in the Stillwater area is dependent on the vertical hydraulic conductivity of the least permeable deposits. An initial estimate for vertical hydraulic conductivity of clay in the Stillwater area is 6.0×10^{-3} ft/d and is based on an average value estimated for clay beneath a playa in central Nevada (Thomas and others, 1989, p. 14). Vertical hydraulic conductivity of the clay that separates the shallow and intermediate aquifers is simulated implicitly, and is incorporated into a leakance term, where leakance is the ratio of vertical hydraulic conductivity of the clay divided by the thickness of the clay (Lohman, 1972, p. 30).

The leakance term is represented in MODFLOW with the following equation (McDonald and Harbaugh, 1988, chap. 5, p. 16):

$$VCONT = 1/(K_z/z) = K_z/z \qquad (3)$$

where $VCONT$ is leakance term, in reciprocal days;

z is thickness of clay between shallow and intermediate aquifers, in feet; and

K_z is vertical hydraulic conductivity of clay, in feet per day.

The thickness of clay between the shallow and intermediate aquifers was estimated to be about 80 ft. This value is based on the maximum thickness of confining beds 1 and 3 from Morgan (1982, p. 25-26). Thus, an initial estimate of leakance used between the shallow and intermediate aquifers is 7.5×10^{-5} per day. This value was adjusted during simulations until computed vertical gradients between the aquifers approximated vertical gradients estimated by Morgan (1982).

Model Calibrations

The models were not designed to exactly replicate ground-water flow in each area because records of long-term changes in ground-water levels, surface-water flows, and irrigation applications were insufficient to provide accurate information for initial conditions and calibration. The strategy for calibration therefore was to approximate ground-water levels and flows for a normal year, and to replicate seasonal fluctuations in the water table while simulating seasonally varying seepage to drains and evapotranspiration. The models were calibrated by changing the hydraulic properties; the hydraulic conductance terms used to simulate flow between surface water and ground water; and the ET extinction depth. During calibration, modeled values were adjusted by small increments until simulated ground-water levels approximated observed ground-water levels and gradients in both areas, and seepage to drains were within estimated limits.

Water Levels

Hydraulic conductivity was varied between 10 ft/d and 30 ft/d for interchannel deposits and between 100 ft/d and 120 ft/d for channel deposits in the Fallon area. Increasing hydraulic conductivity lowered simulated water levels. Increasing the ET extinction depth from 10 to 15 ft also resulted in lower water levels. Increasing specific yield (storage coefficient) from 0.15 to 0.20 for interchannel deposits and from 0.20 to 0.26 for the channel deposits reduced seasonal water-level fluctuations. Reducing hydraulic conductivity of the canal bed by a factor of 10 caused decreased seepage from canals, and a corresponding decrease in ground-water levels of at least 1 ft.

Seasonal fluctuations of ground-water levels in the Fallon area generally replicated observed fluctuations (fig. 13) when horizontal hydraulic conductivity of interchannel deposits was 10 ft/d and channel deposits was 100 ft/d. For this simulation, vertical hydraulic conductivity of canal bed was 1 ft/d throughout the model area. Seepage rates in canals that had an assigned vertical hydraulic conductivity of 10 ft/d exceeded rates measured at several locations (Bureau of Reclamation, 1994, appendix B). The large seepage rates also produced flows in drains that exceeded measured flows.

Slight differences in simulated versus measured water levels could result from differences in the timing of applied irrigation as opposed to those simulated in the model or to locally varying aquifer properties not simulated in the model. For the simulation, specific yield was 0.20 for interchannel deposits and 0.26 for channel deposits, and the ET extinction depth was 10 ft. Simulated water levels show a repeatable pattern that indicates a state of dynamic equilibrium (fig. 13).

The distribution of simulated water levels in the Fallon area varied during each year and was dependent on the timing of water released into canals and applied irrigation. The distribution of water levels for the end of March and end of August are shown in figure 14. The distribution shows the effects of canals and drains on water levels in the shallow aquifer. Considerably more detail is simulated in the area than is shown on the regional map of ground-water levels in the shallow aquifer (fig. 3; Seiler and Allander, 1993, p. 17). The overall water-level gradient between the northwest corner, where water levels generally are highest, and southeast corner, where water levels are lowest, is 8.6 ft/mi. This gradient includes the steep decline in water levels at the southeast corner resulting from the drainage ditch having been excavated 20 ft below land surface. Excluding the southeast corner, the water-level gradient in the Fallon area is about 5.5 ft/mi, which approximates the general gradient of 6 ft/mi determined from observed water levels in the area (Seiler and Allander, 1993, p. 17). Water levels generally are higher at the end of August than in March.

Hydraulic conductivity of the shallow aquifer (model layer 1) in the Stillwater area was varied between 2.5 ft/d and 7.5 ft/d for interchannel deposits and between 25 ft/d and 75 ft/d for channel deposits. Increasing and decreasing the hydraulic conductivity of both deposits had little effect on the simulated water levels. Reducing the hydraulic conductivity of the canal bed by a factor of 10 decreased seepage into the aquifer and consequently decreased water levels slightly.

Seasonal fluctuations in water levels in the Stillwater area generally replicated observed fluctuations when horizontal hydraulic conductivity of interchannel deposits was 5 ft/d and channel deposits was 50 ft/d. For this simulation, the vertical hydraulic conductivity for the canal bed was 1 ft/d for interchannel deposits and 10 ft/d for channel deposits. Specific yield and ET extinction depth were the same as used in the model of the Fallon area. Only one observation well is monitored in the Stillwater area; however, simulated and observed seasonal fluctuations were similar (fig. 13*C*). The distribution of water levels in the Stillwater area for the end of March and end of August are shown in figure 15. Generally, water levels in the shallow aquifer mimic the shape of the land surface with highest in the south and declining toward the north. Water levels at the end of August are higher than at the end of March. The effect of canals and drains in the Stillwater area are not as pronounced as those in the Fallon area mostly because of lower hydraulic conductivities in the shallow aquifer and because the drains are shallower in the former area. The overall modeled water-level gradient in the Stillwater area is about 5 ft/mi and is similar to the estimated gradient of about 6 ft/mi (Seiler and Allander, 1993, p. 17).

Horizontal hydraulic conductivity of the intermediate aquifer (layer 2) in the Stillwater area was adjusted until a uniform gradient was simulated throughout the layer. Assuming a 450-ft thick aquifer, hydraulic conductivity was varied between 1 and 100 ft/d. Increasing hydraulic conductivity caused the head gradient to become more uniform throughout the

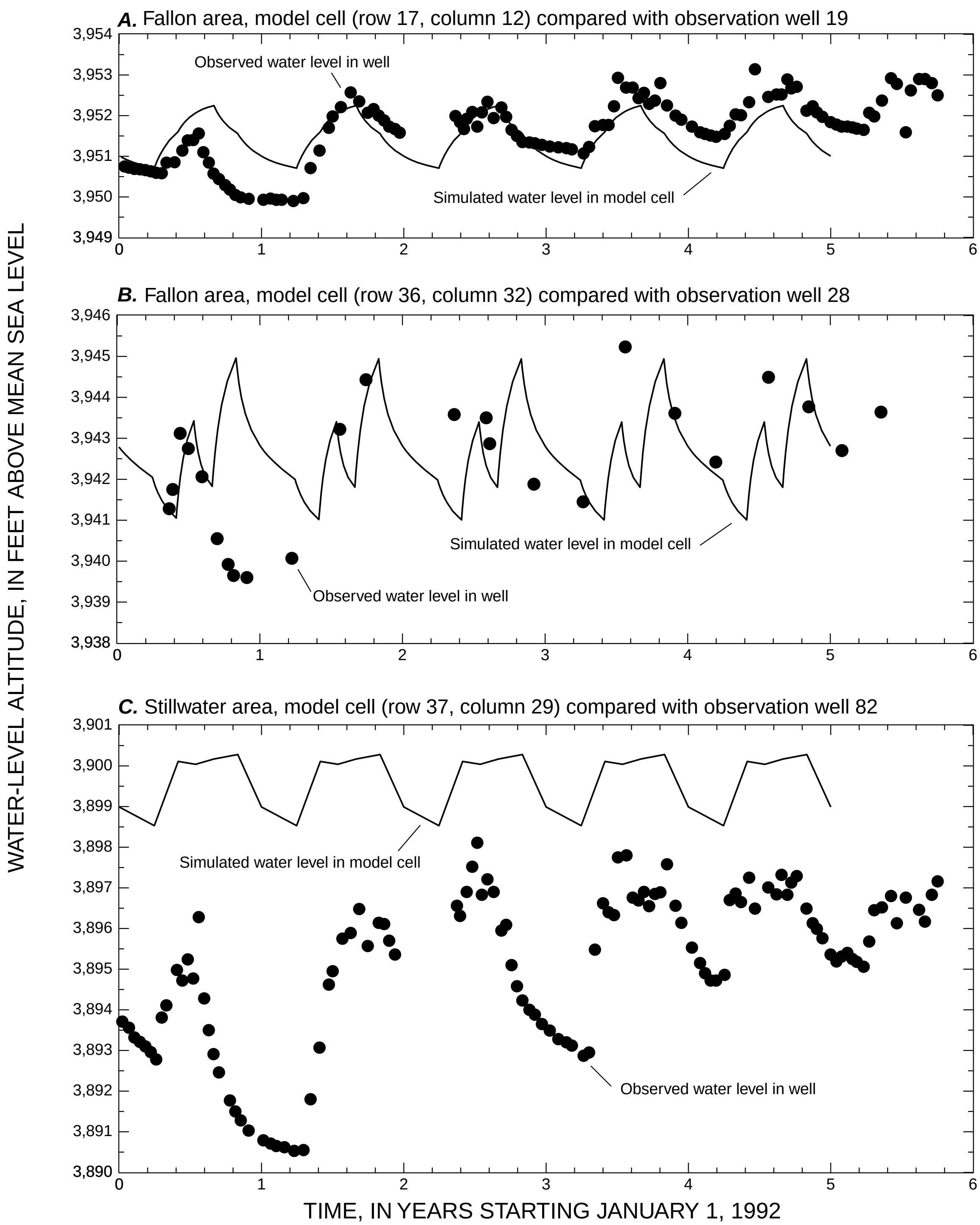


Figure 13. Comparison of water levels measured in three observation wells with water levels simulated in corresponding cells for models of Fallon and Stillwater areas, Nevada. Location of observation wells is shown in figures 14 and 15.

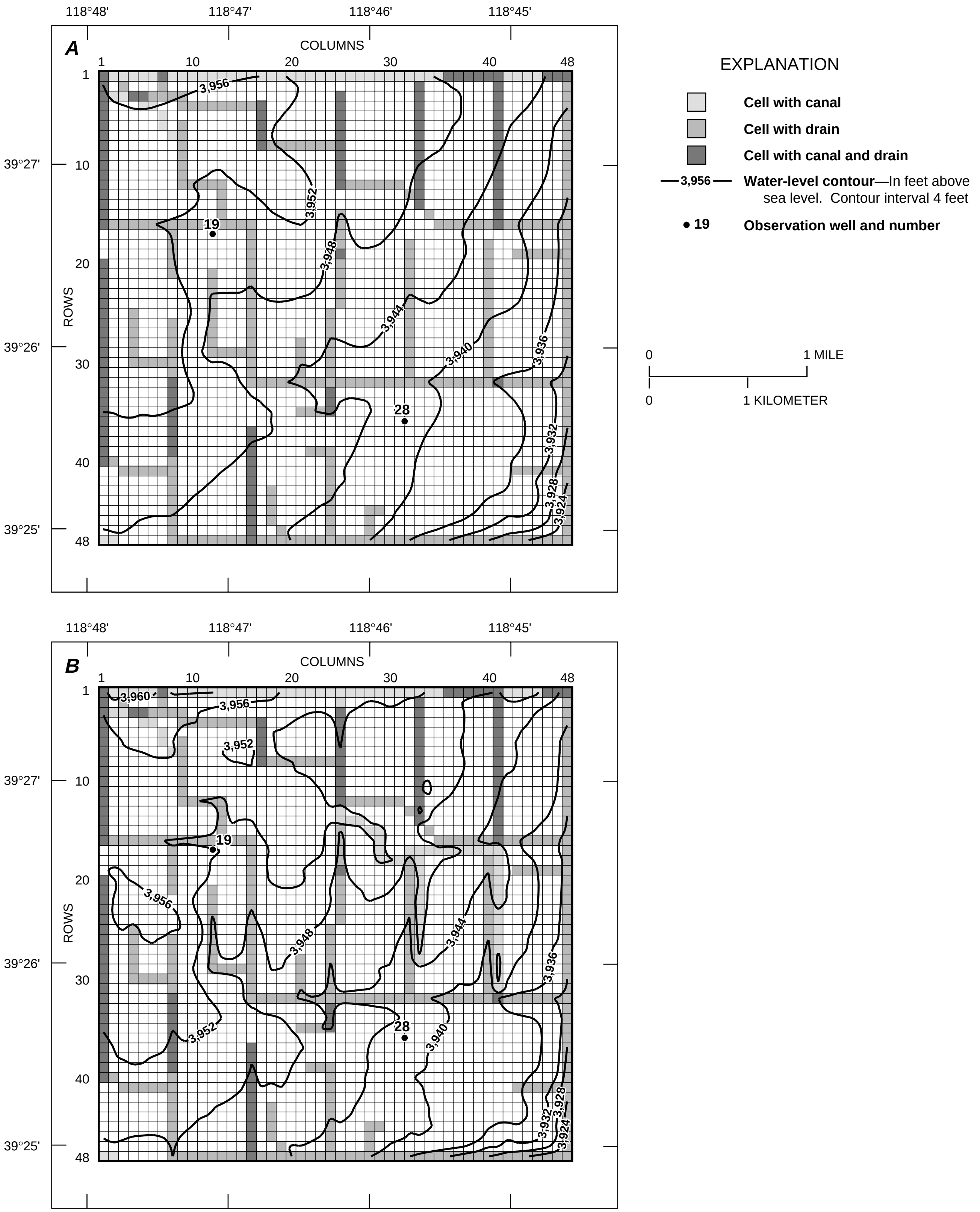


Figure 14. Simulated water levels in shallow aquifer (***A***) at end of stress period 25 (March 31 of year 5) and (***B)*** at end of stress period 28 (August 31 of year 5) for model of Fallon area, Nevada.

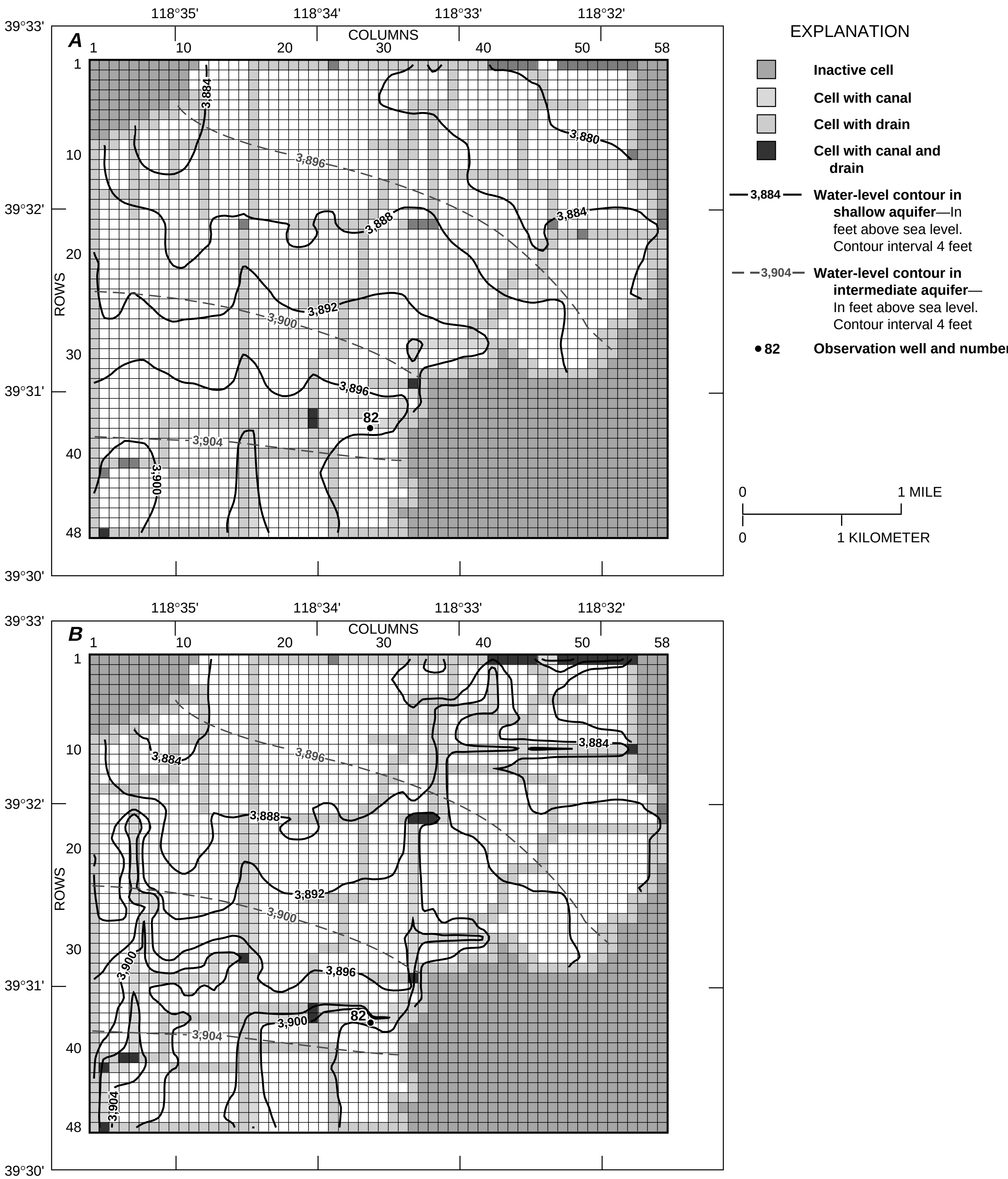


Figure 15. Simulated water levels in shallow and intermediate aquifers (***A***) at end of stress period 25 (March 31 of year 5) and ***(B)*** at end of stress period 28 (August 31 of year 5) for model of Stillwater area, Nevada.

aquifer. The most reasonable value was about 4 ft/d (a transmissivity of 2,000 ft^2/d). Simulated water levels for the intermediate aquifer are shown in figure 15.

The vertical leakance between model layers (shallow and intermediate aquifers) was adjusted until the gradient between shallow and intermediate aquifers approximated the observed upward gradient. Vertical leakance was varied between 4.3×10^{-7} per day and 4.3×10^{-9} per day. A leakance of 4.3×10^{-8} per day produced the most reasonable fit to the observed upward gradient. In the Stillwater area, the maximum upward gradient of 0.11 ft/ft was in the northeast and the minimum upward gradient of 0.03 ft/ft was in the southwest. Most of the modeled area has upward gradients between 0.04 ft/ft and 0.06 ft/ft. Measured upward gradient in the Stillwater area is approximately 0.04 ft/ft (Morgan, 1982, p. 45). Upward flow from the lower layer over the modeled area of 8.7 mi^2 was about 0.11 ft^3/s (76 acre-ft/yr; table 4). The estimated upward geothermal flow into the intermediate aquifer over an area of 39 mi^2 is about 1,300 acre-ft/yr (Morgan, 1982, p. 50 and table 13). Assuming upward flow is similar over the entire area, upward flow for an area of 8.7 mi^2 would be about 290 acre-ft/yr. Much of the upward flow into the intermediate aquifer moves laterally northward through the sandy deposits (Morgan, 1982, p. 83), thus, the simulated rate of 76 acre-ft/yr between the intermediate and shallow aquifer is reasonable.

Flow

In addition to ground-water levels, simulated seepage from canals and to drains were compared to estimated seepage rates. When these simulated values were within reasonable limits, calibration was considered complete. Calibrating the models to measured recharge and discharge is difficult because actual quantities are unknown. Estimates of maximum ET rates and depth of extinction assigned to the models are based on previous studies (see section Evapotranspiration). Similarly, recharge rates from applied irrigation also are based on previous studies of crop consumption (see section Applied Irrigation and Precipitation). Ponded seepage measurements were obtained in 1992 and 1993 at 10 locations along lateral canals to estimate canal losses in different areas of the Newlands Project (Bureau of Reclamation, 1994, appendix B). The ponded seepage measurements were used to compare with seepage rates simulated in both modeled areas.

A simulated ground-water budget was determined for the modeled areas (table 4). Lateral ground-water inflow was not simulated separately in the shallow aquifer due to the relatively small influence when compared with recharge from canals and discharge to drains. Simulated water budgets for the fifth year represent a dynamic equilibrium as budget values were the same between simulation years 4 and 5.

Table 4. Ground-water budgets of shallow aquifer for a typical year on basis of baseline simulations of Fallon and Stillwater areas, Nevada

[Symbol: <, less than. Values in acre-feet per year, rounded to three significant figures for values greater than 100, and rounded to nearest acre-foot for values less than 100]

Component	Fallon		Stillwater	
	Budget	Percent of total budget	Budget	Percent of total budget
Inflow				
Recharge from applied irrigation	5,260	37	4,540	40
Recharge from precipitation	667	5	577	5
Seepage from canals	7,990	56	5,380	47
Seepage from drains	298	2	881	8
Flow from intermediate aquifer	--	--	76	< 1
Total inflow	14,200	100	11,500	100
Outflow				
Evapotranspiration	6,500	46	9,890	86
Seepage to canals	78	< 1	16	< 1
Seepage to drains	7,570	53	1,540	13
Withdrawals from domestic wells	63	< 1	7	< 1
Total outflow	14,200	99	11,500	99
Change in storage	0	--	0	--

The ground-water budget also indicates that the transient models reach a dynamic steady state by the end of the simulation because changes in the annual storage component are less than 1 acre-ft/yr, or less than 0.01 percent of the annual water budget.

Simulated inflow to the Fallon area was approximately 14,200 acre-ft/yr (56 percent from canal seepage, 37 percent from applied irrigation, 5 percent from precipitation, and about 2 percent from drains). Total outflow also was 14,200 acre-ft/yr (53 percent seepage to drains, 46 percent by ET, and less than 1 percent each of withdrawals from wells and seepage to canals).

Simulated inflow to the Stillwater area was approximately 11,500 acre-ft/yr (47 percent from canal seepage, 40 percent from applied irrigation, 8 percent from drains, 5 percent from precipitation, and less than 1 percent upward flow from the intermediate aquifer). Total outflow also was 11,500 acre-ft/yr (86 percent by ET, 13 percent seepage to drains, and less than 1 percent each of withdrawals from wells and seepage to canals). In comparison, Chambers and Guitjens (1995) estimated that about 54 percent of inflow to the shallow aquifer is from applied irrigation at the headgate (includes small canals in fields) and 46 percent is from canal seepage for the entire Newlands Project area. They also estimated that outflow was evenly divided between ET and seepage to drains. In this study, the difference in percentage between the Fallon and Stillwater areas is due primarily to the difference in hydraulic conductivity used in the models and the depth of drains. In particular, greater discharge by ET was simulated in the Stillwater area due to the lower hydraulic conductivities, and the shallower depth of drains.

Measured seepage rates were less than 0.5 ft/d for a section of one lateral canal in the Stillwater area and ranged from 0.2 to 5.8 ft/d for four sections of lateral canals in the Fallon area (Bureau of Reclamation, 1994, appendix B). The variations in rates were governed by variations in canal water depth and time of year. Rates were highest at the beginning of the irrigation season following the winter when canals were dry. Simulated seepage rates for sections of canals that corresponded to the test locations were about 1 ft/d in the Stillwater area and ranged from 2.5 to 3.1 ft/d in the Fallon area. These results suggest that simulated seepage rates from canals in the Stillwater area may be slightly high and thus, the estimates of hydraulic conductivity of either the canal bed or the shallow aquifer are too high. However, the results are based on only one measured section of canal that had been excavated in fine-grained sediments. Other canals could be excavated in coarser deposits and thereby have much greater seepage rates than that measured. Because the model simulates average properties of two types of deposits—interchannel and channel—simulated seepage rates are more uniform than what actually may occur.

During this study, flow in drains entering and leaving the modeled areas were measured to compare with simulated seepage to drains. In the Fallon area, all drain flows originate within the modeled area. Flow in the two drains at the southeast corner of the model were measured twice during an irrigation season (June 3, 1997, and Aug. 21, 1997). These two drains represent all of the discharge from drains in the modeled area. Total measured flows were 36 ft^3/s for June 3 and 15.6 ft^3/s for Aug. 21. Total simulated drain flow for the end of May was 12.2 ft^3/s and for end of August was 15.0 ft^3/s. Measured drain flows are more than simulated drain flows because overland flow from the fields or overflow from canals contribute to drain flow and are not simulated in the model. Simulated discharge to drains ranged from 2.7 ft^3/s at the end of March to 16.5 ft^3/s on July 15.

Measurements of discharge from drains in the Stillwater area are complicated because considerable drain flows originate from areas outside of the modeled area and because three major drains exit the northern boundary of the modeled area (fig. 8). Total simulated seepage between ground water and drains ranged from a net recharge of 0.6 ft^3/s on July 15 (stress period 27) to a net discharge of 4.1 ft^3/s on Aug. 31 (stress period 28). The drains generally provide a net recharge to ground water from 0.3 to 0.4 ft^3/s during the winter months (Nov. through Mar.). This is consistent with the concept that drains can be a source of recharge to the shallow aquifer in the eastern part of the Carson Desert (fig. 5*B;* Maurer and others, 1996, p. 82). Flow in the drain at the northwest corner of the model was measured at 11.4 ft^3/s on June 3, 1997. Flows entering the drain from outside the modeled area were nearly the same, thus the quantity of ground-water seepage to this drain is minimal. Flow in the drain at the north boundary of the model was measured at 12.5 ft^3/s on Aug. 21, 1997. Much of this flow originates within the modeled area as either surface runoff or as ground-water seepage. Flow in Stillwater Slough along the eastern model boundary was measured at 23 ft^3/s on the southeast boundary and at 33 ft^3/s on the northeast boundary on Aug. 23, 1997, indicating that drain flow increased 10 ft^3/s. This increase results from a combination of surface-water runoff and ground-water seepage along both sides of the drain. The quantity of ground-water seepage to drains within the modeled area is difficult to determine because of the contribution of flows from outside the modeled area and from surface-water drainage. Consequently, simulations having drain flows less than measured flows were considered acceptable.

Much of the ground-water flow in both modeled areas is focused in the more permeable channel deposits. Analyses using MODPATH (Pollock, 1994) suggests that the channel deposits act as conduits of flow to the drains. Although average ground-water flow in the shallow aquifer can be estimated using average hydraulic properties, the distribution of the channel deposits is important in understanding potential flow paths for water.

Sensitivity Analyses

Several variables used in the simulations were tested for sensitivity with respect to water levels and flows. Variables tested for the Fallon area were canal-bed hydraulic conductivity (K_c), drain-bed hydraulic conductivity (K_d), maximum ET rate (ET_{max}), ET extinction depth, recharge from precipitation, withdrawals from wells, and hydraulic conductivity of the interchannel deposits. In addition to the variables tested in the Fallon area, vertical hydraulic conductivity between the shallow and intermediate aquifers and hydraulic conductivity of all deposits were tested for the Stillwater area (table 5). The sensitivity of each variable was tested by uniformly increasing or decreasing one value and determining the change in water levels and flows from the calibrated simulation.

Increasing the ET extinction depth from 10 to 20 ft (factor of 2) produced the largest average change in ground-water levels in both modeled areas (table 5). Decreasing well withdrawals from 300 to 60 gal/d (factor of 0.2) and recharge from precipitation to near zero in the Fallon area produced the least changes. Doubling the ET extinction depth greatly increased discharge by ET and reduced seepage to drains (figs. 16 and 17). Decreasing ET_{max} by 50 percent caused an opposite effect in that ET decreased and seepage to drains increased. Decreasing canal- and drain-bed hydraulic conductivity reduced seepage from canals, and seepage to drains and ET (figs. 16 and 17), yet the water levels on average changed less than 1 ft (table 5). Decreasing the hydraulic conductivity of the canal bed alone reduced seepage from canals and generally decreased water levels, whereas, decreasing hydraulic conductivity of the drain bed reduced seepage to drains and caused a rise in water levels and a corresponding decrease in canal seepage. Increasing the hydraulic conductivity of the interchannel deposits generally resulted in minimal water-level changes.

In the Stillwater area, flow from the intermediate to shallow aquifer is increased most when the ET extinction depth is increased and when hydraulic conductivity of both aquifers is doubled (fig. 17). Flow between aquifers is less when the maximum ET rate is reduced because water levels in the shallow aquifer are higher and consequently, less difference in water levels exists between aquifers. Changing any of the variables in the Stillwater area causes changes in seepage to drains. One possible explanation for the relatively large changes in seepage to drains is that small changes in water levels in the shallow aquifer causes the drains to alternate between a source and a sink.

Limitations of Models

The modeled areas in this report are based on a simplified set of assumptions representing a complex physical system. The accuracy of the flow model is based upon several critical assumptions: (1) lateral ground-water flow into or out of the shallow aquifer in each modeled area is minimal; (2) the shallow aquifer can be represented by two distinct deposits that are uniform throughout its thickness; and (3) flow between the shallow aquifer and deeper aquifers is inhibited by an extensive clay layer. The scope of the study was to use existing information to obtain reasonable estimates of hydraulic properties and recharge from applied irrigation. The only data collected during the study were measurements of width, depth, altitude, and slope of canals and drains, and a few flow measurements in selected drains. Thus, models are limited by the accuracy of the assumptions used to model flow in the shallow aquifer, in the uncertainties associated with the use of the available data to represent average properties of the deposits, and in estimating recharge from applied irrigation.

The models are designed to simulate ground-water levels and flows within limited areas of the Newlands Project. Modeled areas were divided into cells 330 ft on a side and the properties within each cell are assumed uniform and homogeneous over an area of 2.5 acres. Although each modeled area is divided into small cells, uncertainties in aquifer properties and in recharge and discharge within each cell do not allow actual predictions of changes in water levels, flows, and water quality at a specific location. Thus, model simulations presented herein are only approximations

Table 5. Sensitivity of simulated water levels to changing selected hydraulic properties and to changing variables for evapotranspiration, recharge from precipitation, and withdrawals from domestic wells for models of Fallon and Stillwater areas, Nevada

[Values in feet]

Selected hydraulic property or model variable	Multiplication factor applied to model variable [1]	Fallon				Stillwater			
		Average change in water level [2]	Standard deviation [3]	Maximum water-level decline	Maximum water-level rise	Average change in water level [2]	Standard deviation [3]	Maximum water-level decline	Maximum water-level rise
Canal-bed hydraulic conductivity (K_c)	0.1	0.5	0.9	8.4	0.3	0.6	1.0	8.7	0.0
Canal- and drain-bed hydraulic conductivity (K_{c+d})	.1	.4	.9	7.8	1.8	.7	1.1	8.7	1.1
Drain-bed hydraulic conductivity (K_d)	.1	-.3	.5	2.5	5.8	.1	.4	3.1	6.0
Maximum evapotranspiration rate (ET_{max})	.5	-.7	.6	.0	2.8	-1.4	1.1	.0	5.4
Evapotranspiration (ET) extinction depth	2	3.2	2.0	8.7	.0	3.0	2.5	9.6	.0
Hydraulic conductivity of interchannel deposits	2	.2	.4	2.4	1.9	-.1	.3	1.2	2.1
Hydraulic conductivity of all deposits [4]	2					-.4	.4	.9	4.9
Recharge from precipitation [5]	[6]2E-07	.1	.1	1.9	.0	.1	.1	1.0	.0
Well withdrawals	.2	.0	.0	.0	.3				

[1] Values less than one result in a decrease in model variable; whereas, values greater than one result in an increase in model variable.

[2] Weighted average water-level change during fifth year of simulation. Positive values indicate a decrease in water levels; whereas, negative values indicate an increase in water levels.

[3] Represents deviations of water-level changes during six stress periods of fifth year of model simulations from weighted mean.

[4] Includes horizontal hydraulic conductivity of deposits in shallow and intermediate aquifer, vertical hydraulic conductivity between aquifers, and vertical hydraulic conductivity of canal and drain beds.

[5] Recharge from precipitation decreased to nearly zero.

[6] 2E-07 is 0.0000002

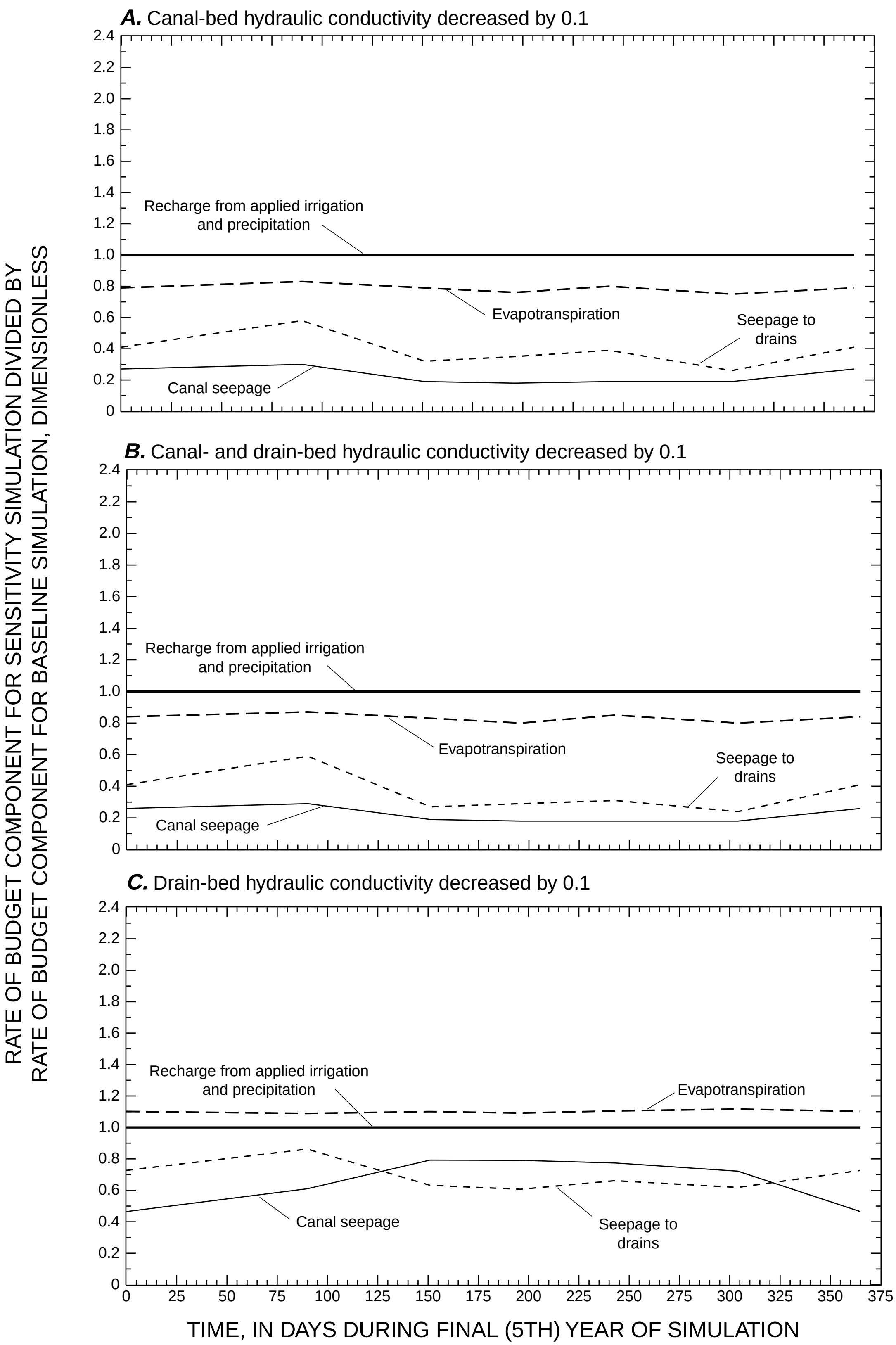


Figure 16. Simulated response of budget components in relation to baseline simulation for each time period during fifth year caused by changing selected variables in model of Fallon area, Nevada.

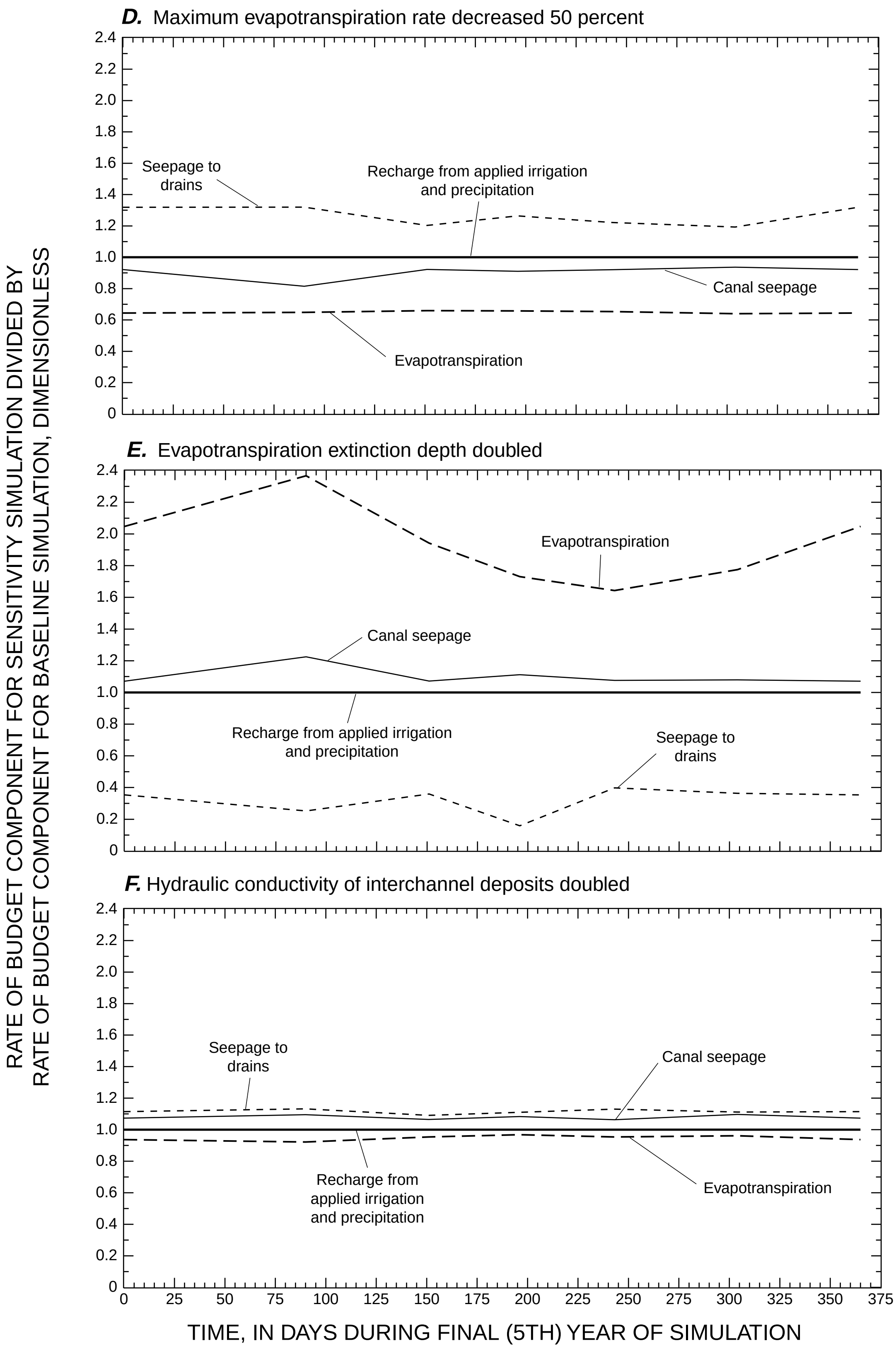


Figure 16. Continued.

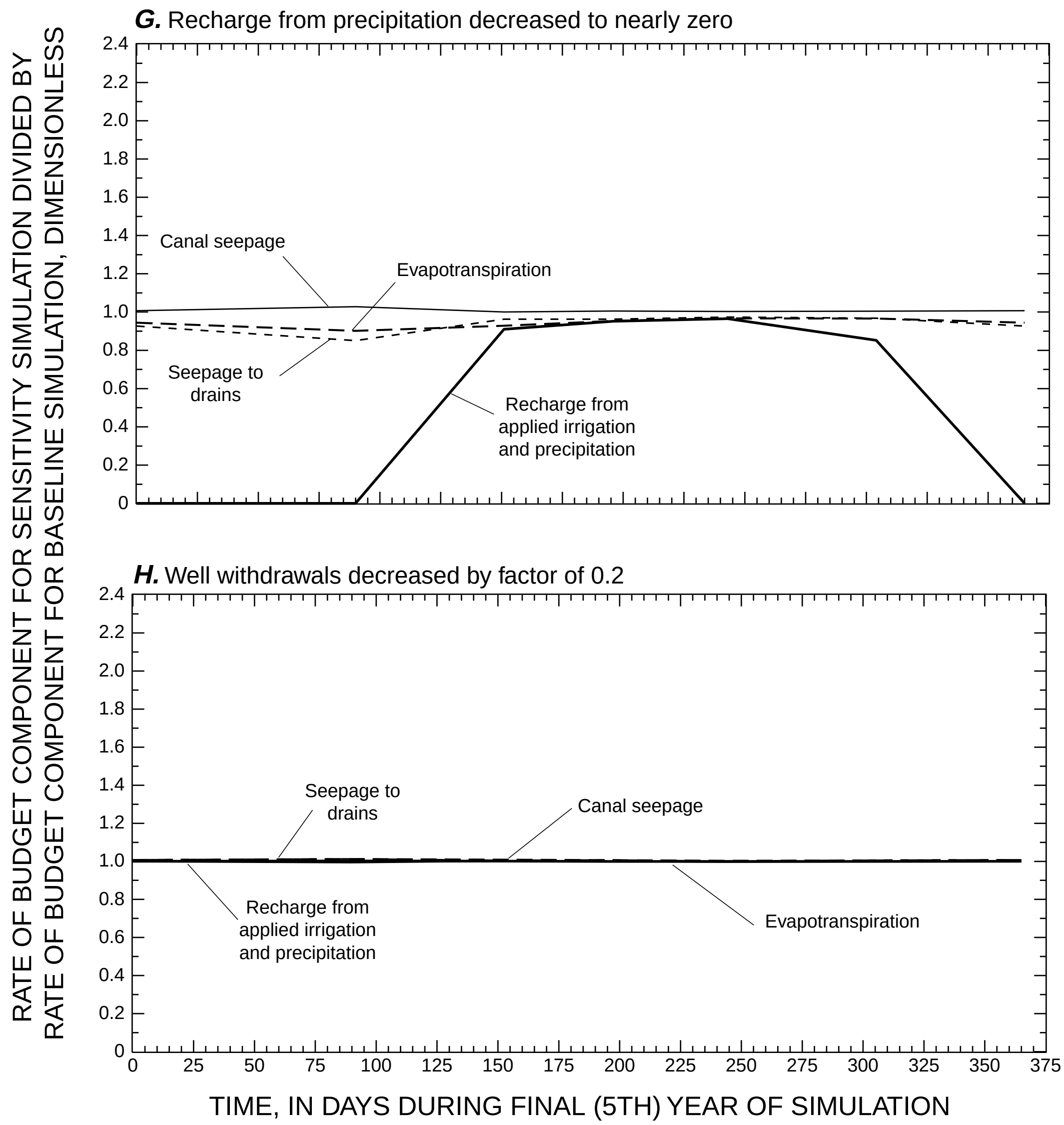


Figure 16. Continued.

to actual occurrences in areas similar to those modeled. Overall, the models replicate ground-water levels and gradients in the Fallon and Stillwater areas.

Results of the models are based on the assumption that full entitlement of 42 in/yr is always available for irrigation and that each irrigated field uses its full entitlement. Actual recharge likely varies from field to field depending on how a farmer applies water to the fields and on the soils that are present. Results also are based on the time duration that canals are full of water. Flow and duration data are available only for the main canals, thus, approximations of the duration and depth of water in the lateral canals were used in the simulations. Even knowing the duration and depth of water in canals may not be sufficient to model seepage losses. Usually, seepage losses are greatest when water is first released into the canals because capillary forces then are greater than gravity forces. In the model, maximum seepage losses are simulated only on the basis of gravity forces. Thus, the simulations are not exact representations of actual recharge from canals and because losses are unknown in most of the modeled areas, the volumes of simulated recharge may be different from actual.

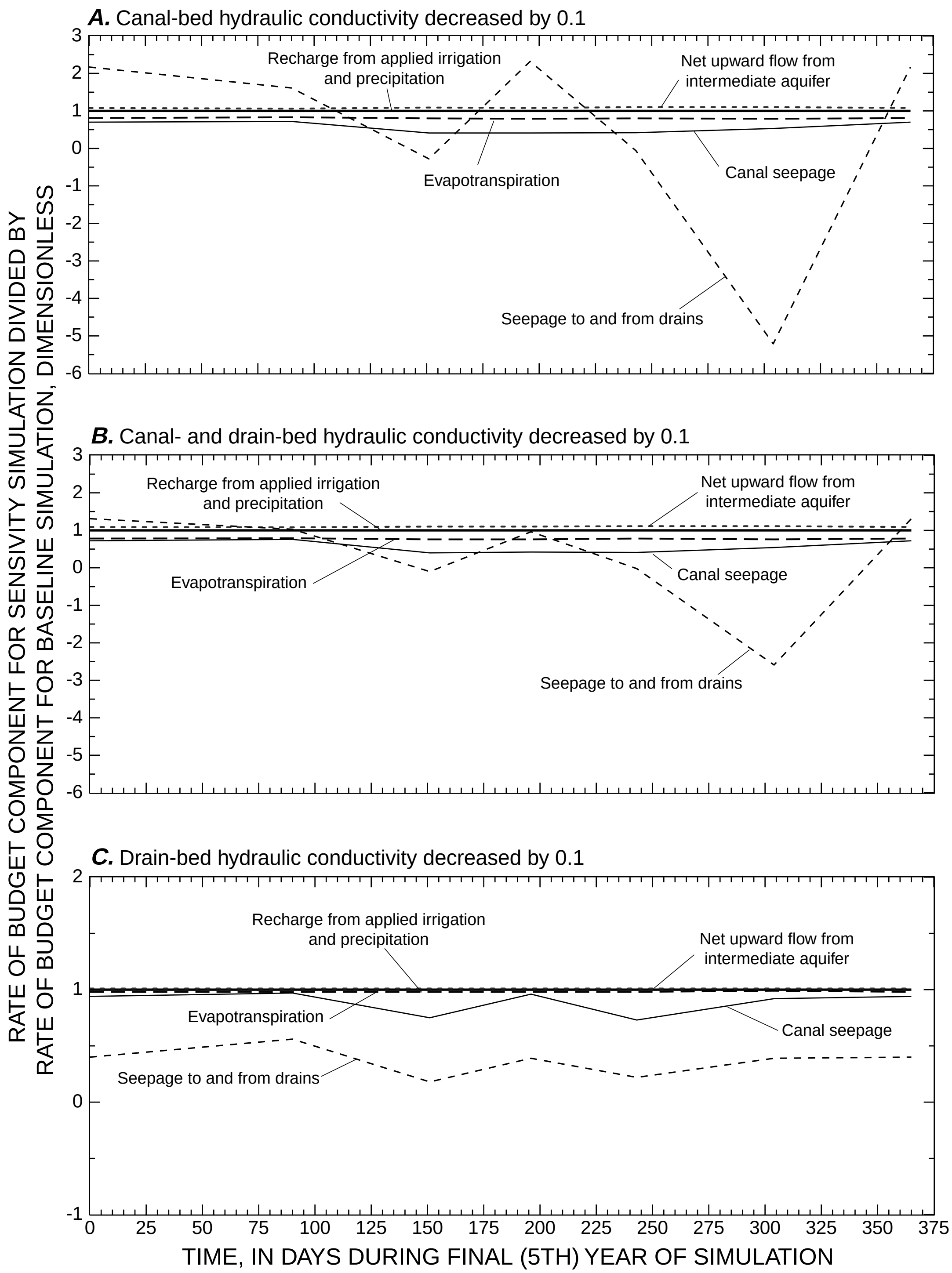


Figure 17. Simulated response of budget components in relation to baseline simulation for each time period during fifth year caused by changing selected variables in model of Stillwater area, Nevada. Negative values of seepage to and from drains represent a net change between ground-water seepage to drains and drain seepage to ground water.

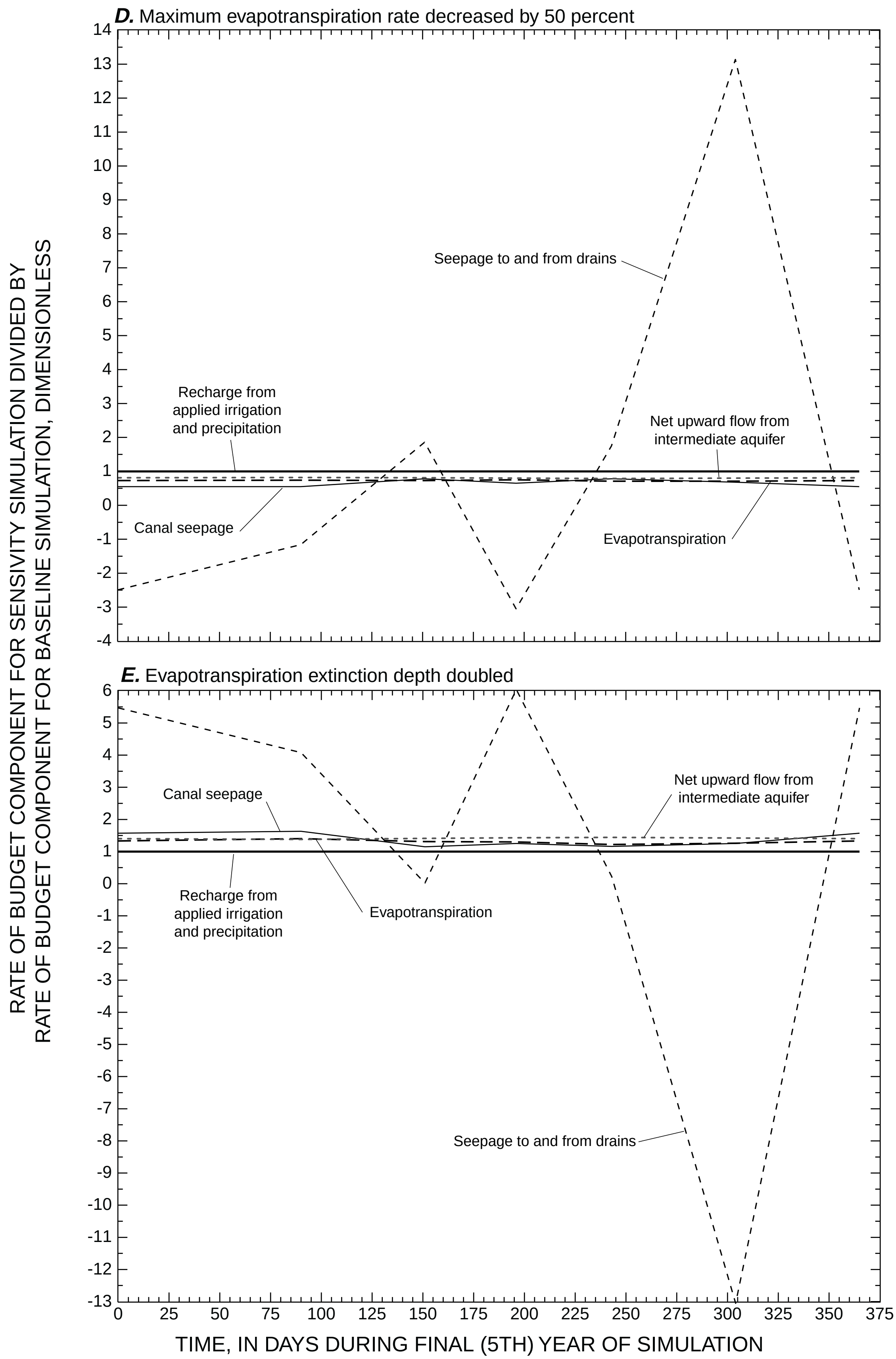


Figure 17. Continued.

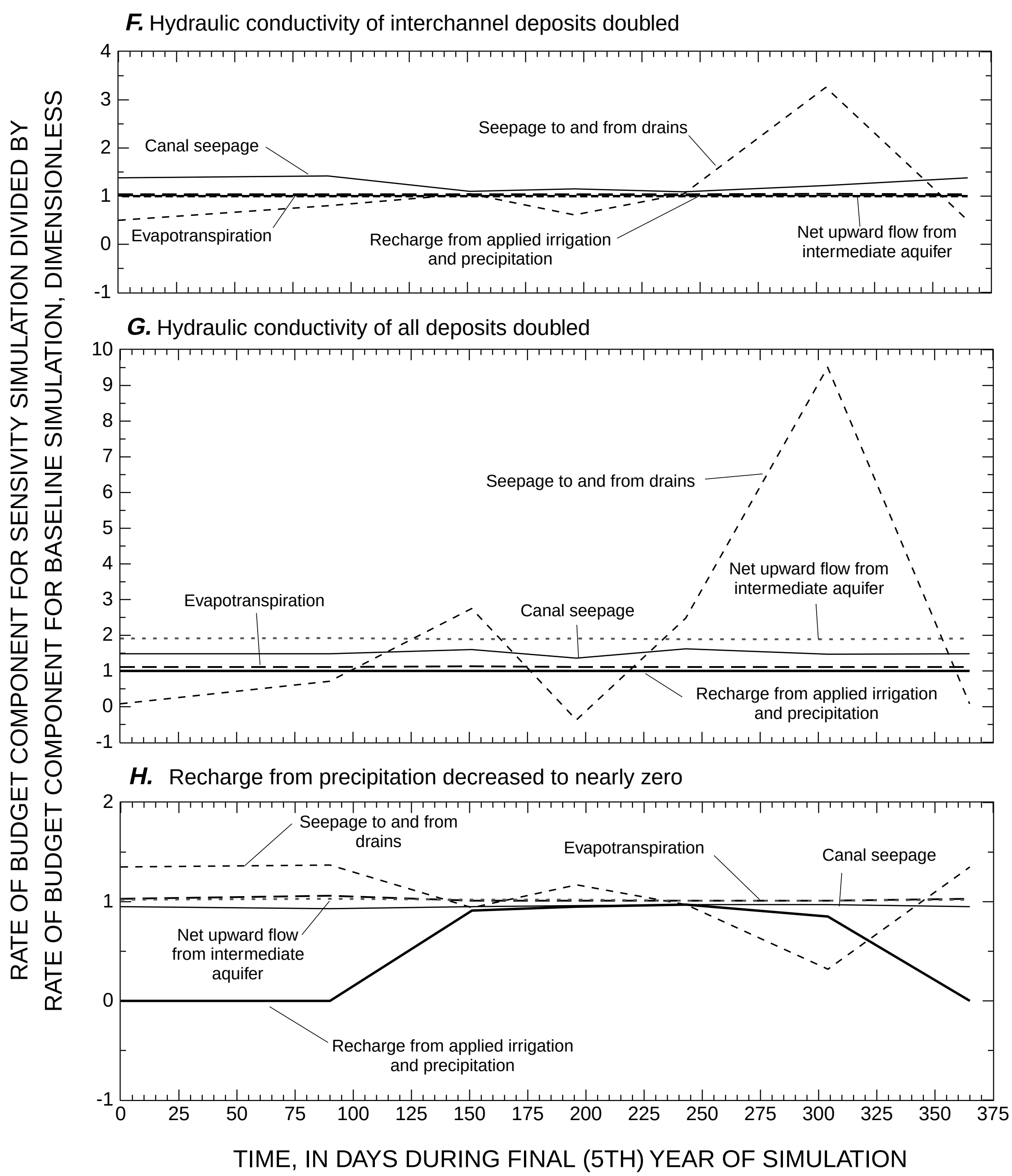


Figure 17. Continued.

The assumption that the aquifer can be divided into two distinct deposits of differing hydraulic properties was done to incorporate observations of previous investigators. However, the distribution of deposits is not as simple as that which was conceptualized in the models. Channel deposits probably exist at depth in more places than exposed at the surface. Conversely, the channel deposits probably do not extend the entire thickness of the shallow aquifer. Furthermore, a considerable percentage of the shallow aquifer consists of fine-grained deposits that are not included in the analyses of hydraulic conductivity from drillers' logs because most wells are screened in the most permeable deposits. How much the finer-grained deposits affect the effective hydraulic conductivity in the shallow aquifer is unknown but hydraulic-conductivity values estimated from drillers' logs were reduced to account for the presence of those fine-grained deposits. Finally, estimates of upward flow from the intermediate aquifer assumes a uniform gradient across a uniform confining unit and that flow is based on water-level differences alone.

The modeled area is within the Stillwater geothermal area and upward geothermal flow into the intermediate aquifer has been documented. This upward geothermal flow is concentrated along fault zones that are present at depth but do not extend to the surface. Upward flow into the shallow aquifer is less than that estimated from geothermal heat flow (Morgan, 1982, p. 50) because much of the upward geothermal flow may move laterally through the intermediate aquifer (Morgan, 1982, p. 83). Even if the quantity of upward flow was increased or focused along a narrow zone to simulate flow along a fault, it would still only be a fraction of the recharge from canals and applied irrigation.

The models are designed to simulate possible effects of changing irrigation practices over relatively small areas (about 1 mi^2). Complete elimination of seepage from canals and recharge from applied irrigation extends beyond the intent of these models because of the assumption that lateral flow into and out of the modeled areas is minimal. If all seepage from canals were stopped, some increase in lateral flow would be likely but could not be simulated with the present model. Thus, the model is designed to simulate the reduction in recharge over an area of about 1 mi^2 while assuming that some water from canals and applied irrigation in neighboring areas recharges the shallow aquifer.

ESTIMATED EFFECTS OF CHANGING IRRIGATION PRACTICES ON GROUND-WATER QUANTITY

Five scenarios were simulated to estimate the possible effects of changing irrigation practices in the Fallon and Stillwater areas on ground-water levels and flow in the shallow aquifer. Model results also were used to estimate effects on ground-water quality, a topic that is discussed in the next section. In each scenario, the quantity of applied irrigation was reduced from current conditions by different techniques. To evaluate the effects of the reductions, ground-water levels and flow budgets for the fifth year of simulation were compared with fifth-year results from the baseline (calibrated) simulation of each area. Changes in quantities of flow were then used to estimate possible effects of changing irrigation practices on ground-water quality. All hydraulic properties, boundary conditions, well discharge, precipitation, and maximum ET rate and ET extinction depth were the same as in the baseline models.

Description of Irrigation Scenarios

Possible future changes to irrigation practices in the Fallon and Stillwater areas are simulated in five scenarios. These scenarios were developed from discussions with representatives from the Bureau of Reclamation and from observations of current land practices in the Fallon and Stillwater areas.

Scenario A—Recharge from Applied Irrigation Reduced 50 Percent

In scenario A, recharge from applied irrigation was reduced by 50 percent throughout each modeled area. Recharge from precipitation was maintained at the baseline rate (1.75 in/yr). This scenario was designed to simulate the results of reducing the total quantity of water received for irrigation applications over the entire irrigation season, while maintaining the full delivery of water in canals throughout the irrigation season in the same manner as that assumed in the baseline simulations. The assumption of this scenario is that less water is available to everyone, a situation that might occur during a prolonged drought.

Scenario B—Recharge Reduced by Shortening Irrigation Season

In scenario B, the irrigation season was shortened to simulate a reduction in applied irrigation. This scenario was designed to simulate full deliveries of water until water was depleted and none was left for irrigation, at which time water deliveries in canals also ceased. The scenario required shortening the time over which canals were full and water was applied to fields. The normal irrigation season in the baseline models was 214 days. However, recharge from applied irrigation varies during the irrigation season (fig. 9). Thus, when a 50 percent reduction in the quantity of applied irrigation was simulated, the irrigation season was reduced to only 91 days. This scenario results in the same reduction in the total applied irrigation for a season as in scenario A, and provides a direct comparison of reducing the rate of applied irrigation for an entire season to reducing the length of the irrigation season.

Scenario C—Recharge Reduced by Removing Applied Irrigation and Precipitation on Half Section of Land

In scenario C, applied irrigation on a half section (total area of 320 acres) was removed in each of the modeled areas. Both recharge from applied irrigation and precipitation during the irrigation season were eliminated within a half section of land selected near the center of each modeled area. Because not all of the half section is irrigated (due to roads, canals, and houses), the actual area of land no longer irrigated varied between the two modeled areas. In the Fallon area, the area removed from irrigation was 292.5 acres, whereas, in the Stillwater area, it was 275 acres. Recharge from precipitation was removed because precipitation in non-irrigated areas is normally lost to evapotranspiration prior to recharging ground water. However, removing precipitation recharge has negligible affect on ground-water levels and flow in the shallow aquifer as reflected in the sensitivity analysis of the baseline models (table 5).

The center location was selected to ensure model results would not be influenced by the edges of each modeled area. This scenario was designed to simulate the effects of removing parcels of farm land from irrigation that continue to be surrounded by farms receiving 100 percent of their entitlements. This scenario is based on the assumption that water deliveries in the main and lateral canals are unaffected by the removal of land from irrigation, and that sufficient irrigated land remains in an area to justify the use of the canal for water deliveries. A half section of land was chosen as the largest parcel of land that would be removed from the sale of a single privately owned farm.

Scenario D—Recharge Reduced by Removing Irrigation and Precipitation and Closing Lateral Canal on Half Section of Land

Scenario D is the same as scenario C except that part of a lateral canal also was closed. This scenario was designed to estimate effects on ground-water levels and flow in the shallow aquifer resulting from the removal of land and closure of a corresponding canal. The scenario is based on the assumption that water in the delivery canal would no longer be used in areas where sufficient land is removed from irrigation.

Scenario E—Recharge from Applied Irrigation Eliminated

In scenario E, recharge from applied irrigation was eliminated, while maintaining recharge from precipitation and water in the main and lateral canals. Although maintaining water in the lateral canals is unlikely if all irrigation in an area ceases, the scenario provides an estimate of the effects of eliminating recharge from applied irrigation over an area larger than 320 acres. This scenario was designed to show changes in ground-water budgets caused by eliminating recharge from irrigation that can be used in analyzing potential effects on water-quality changes. (See section on Estimated Effects of Changing Irrigation Practices on Ground-Water Quality.)

Simulated Effects in Fallon Area

Simulated effects of reducing recharge on ground-water quantity in the Fallon area are discussed in terms of changes in water levels and flow budgets from those of the baseline simulation. Each scenario was simulated for a period of 5 years, which was sufficient to produce a new dynamic equilibrium for each scenario.

Water Levels

Ground-water levels declined from the baseline simulation in each of the five scenarios (table 6; fig. 18). Average water-level declines ranged from

Table 6. Summary of water-level changes for selected scenarios of reduced recharge to shallow aquifer near Fallon and Stillwater, Nevada

[Water levels in feet, rounded to one decimal place]

Scenario	Description of scenario	Fallon				Stillwater			
		Average decline in water level [1]	Standard deviation [2]	Maximum water-level decline	Maximum water-level rise	Average decline in water level[1]	Standard deviation[2]	Maximum water-level decline	Maximum water-level rise
A	Recharge from applied irrigation reduced 50 percent	0.5	0.4	3.2	0.0	0.6	0.6	2.6	0.0
B	Recharge reduced by shortening irrigation season	1.1	1.0	10.3	.9	1.4	1.4	9.9	1.1
C	Recharge reduced by removing applied irrigation and precipitation on half section of land	.1	.3	2.9	.0	.1	.6	4.2	.0
D	Recharge reduced by removing applied irrigation and precipitation and closing part of lateral canal on half section of land	.1	.4	6.4	.0	.2	.7	7.2	.0
E	Recharge from applied irrigation eliminated	1.1	.9	7.1	.0	1.3	1.1	4.1	.0

[1] Weighted average decline during fifth year of model simulation.

[2] Represents deviations of water-level changes during six stress periods of fifth year of model simulation from weighted mean.

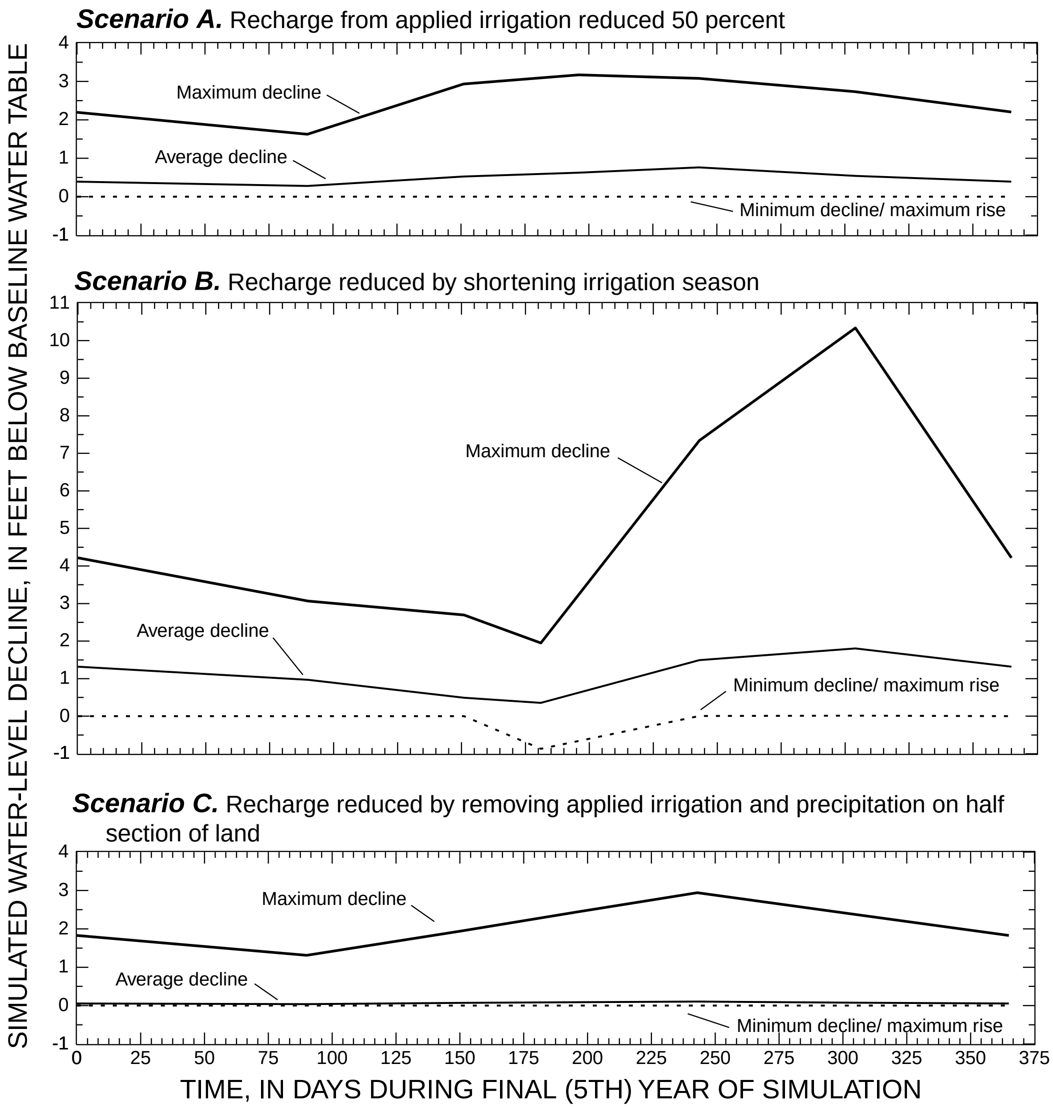


Figure 18. Simulated maximum, average, and minimum water-level declines from baseline simulation for each time period during fifth year for all five scenarios of reducing recharge in model of Fallon area, Nevada.

0.1 to 1.1 ft for the five scenarios, with the largest average decline simulated for scenario E (no recharge from applied irrigation). Standard deviations of 1 ft or less for all scenarios (table 6) suggest that large water-level declines are limited to localized areas and that changes in water levels caused by simulated reductions in recharge generally resulted in small water-level declines. Seasonally, largest water-level declines were simulated during the summer months (compared with baseline simulation), whereas, water-level declines were much less during winter months (fig. 18).

In scenarios where normal delivery of water in canals was maintained (scenarios A, C, and E; fig. 18*A*, *C*, and *E*), maximum water-level declines were simulated in areas most distant from a canal. In contrast, scenarios in which the delivery of water was shortened (scenario B; fig. 18*B*) or where a section of canal was eliminated (scenario D; fig. 18*D*), maximum water-level declines were simulated near canals. Water-level declines of more than 10 ft were simulated near canals during the summer when no water was simulated in the canals (scenario B; fig. 18*B*). Although scenario B produced the largest declines in water levels, the average decline over the 5-year simulation period was only 1.1 ft. Most of the largest water-level declines were simulated adjacent to canals that ceased flowing during the latter part of the normal irrigation season. This indicates that removing sections of a canal could produce

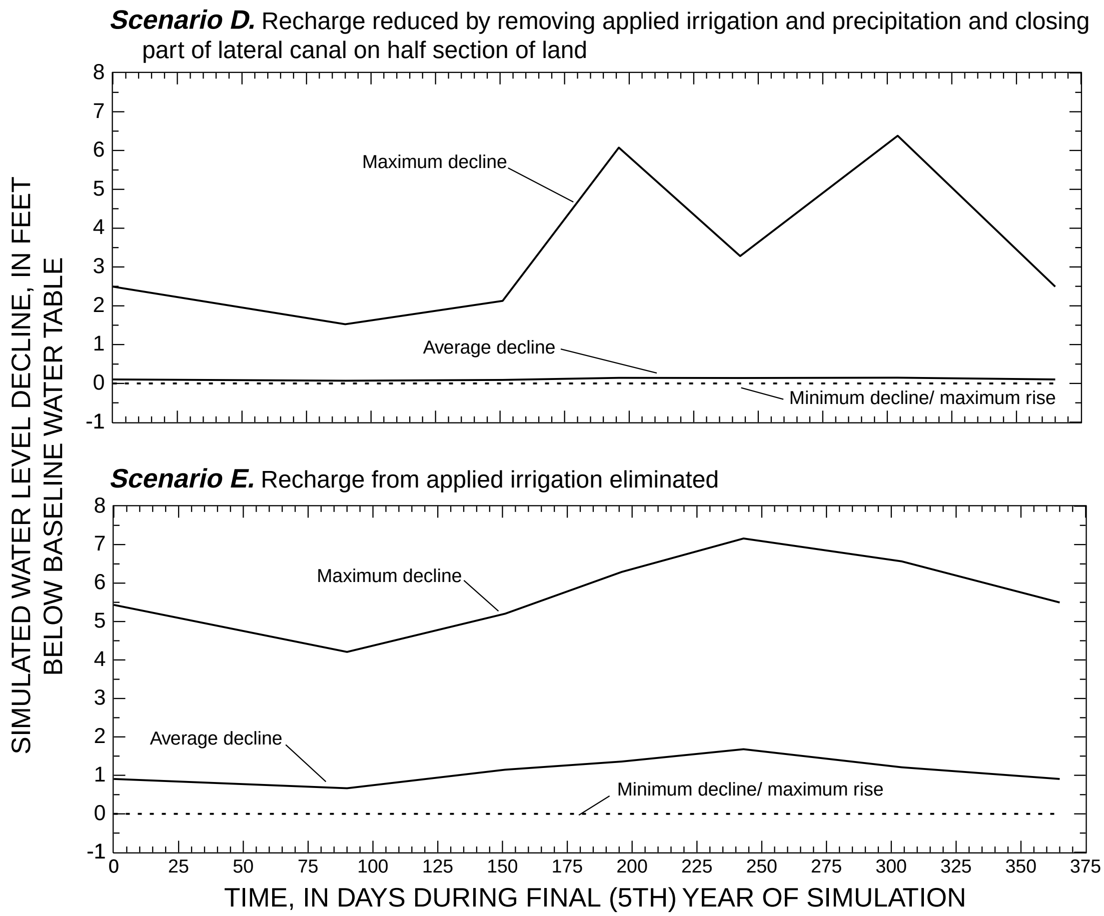


Figure 18. Continued.

large water-level declines next to the canal but would have little effect over a large area, whereas, removing large areas from irrigation would cause a lesser decline in water levels but over a larger area.

Water Budget

Simulated ground-water budget decreased in each of the five scenarios (fig. 19). Changes in ground-water storage between the beginning and end of the fifth year of simulation was nearly zero for the first four scenarios (table 7) indicating that each of these scenarios had reached a new dynamic equilibrium to the simulated changes in irrigation practices. At the end of 5 years, scenarios B and E still showed a slight change in storage that could be caused by some isolated areas of the model not having reached equilibrium after 5 years. However, the change in storage is less than 0.03 percent of the total water budget, thus, even these scenarios virtually have reached a new equilibrium.

Decreasing the recharge rate of applied irrigation by 50 percent (scenario A) resulted in a nearly equal decrease in outflow from seepage to drains and ET, and slight increases in inflow from canal and drain seepage (table 7, fig. 19*A*). The greatest decrease in the ground-water budget was simulated when the irrigation season was shortened (scenario B; table 7). Shortening the irrigation season (scenario B) greatly reduced recharge from canal seepage during the summer months and resulted in greater seasonal fluctuations in the water-budget components (fig. 19*B*). Results from this scenario indicate that budget components were little affected during the shortened irrigation season but were quickly reduced to flows similar to the winter season once water deliveries in canals ceased.

The ground-water budget was affected least when irrigation for a half section of land was removed (scenario C; table 7; fig. 19*C*). Recharge from applied irrigation and precipitation was decreased about 385 acre-ft/yr, which resulted in a slightly greater decrease in

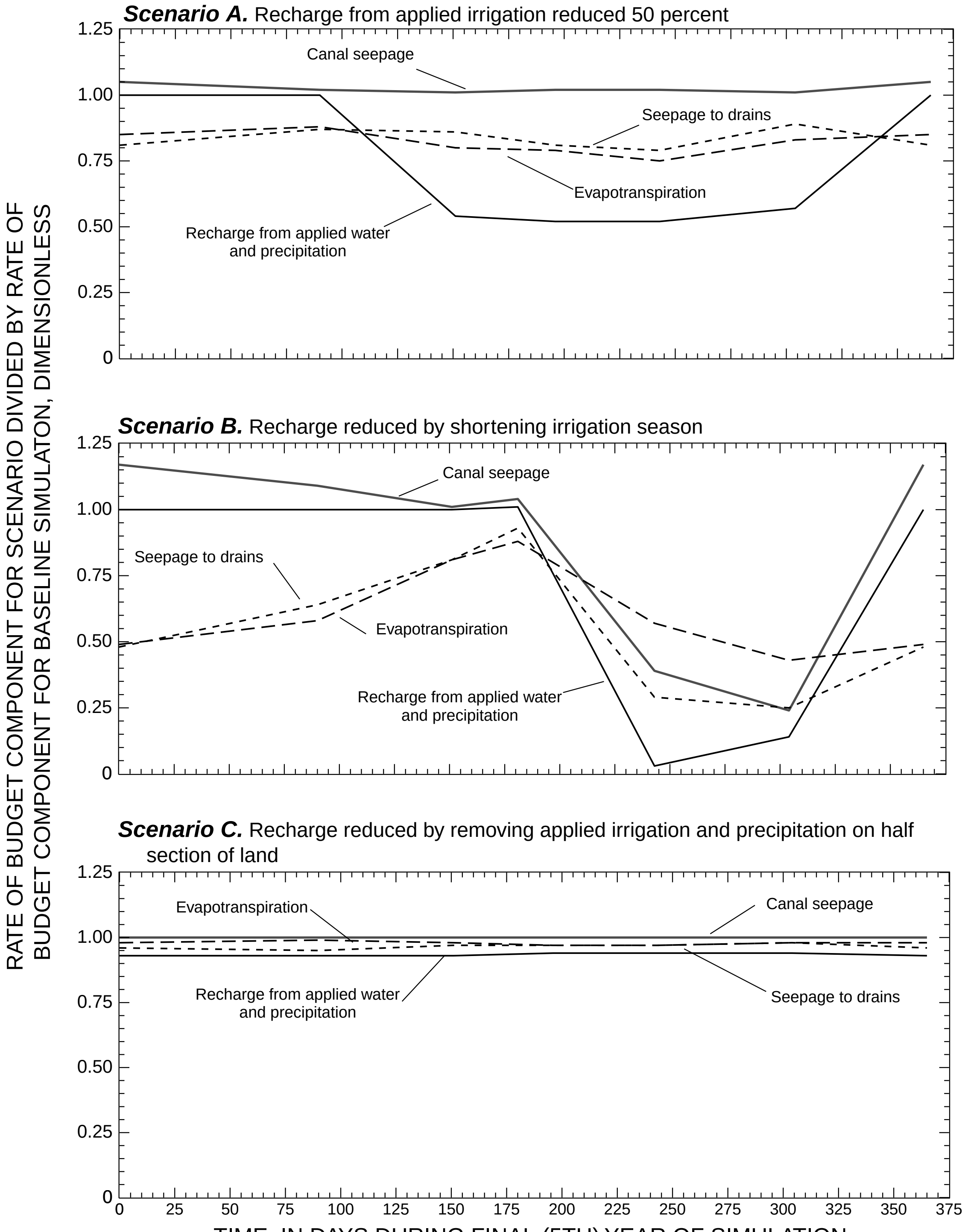


Figure 19. Simulated response of budget components in relation to baseline simulation for each time period during fifth year for all five scenarios of reducing recharge in model of Fallon area, Nevada.

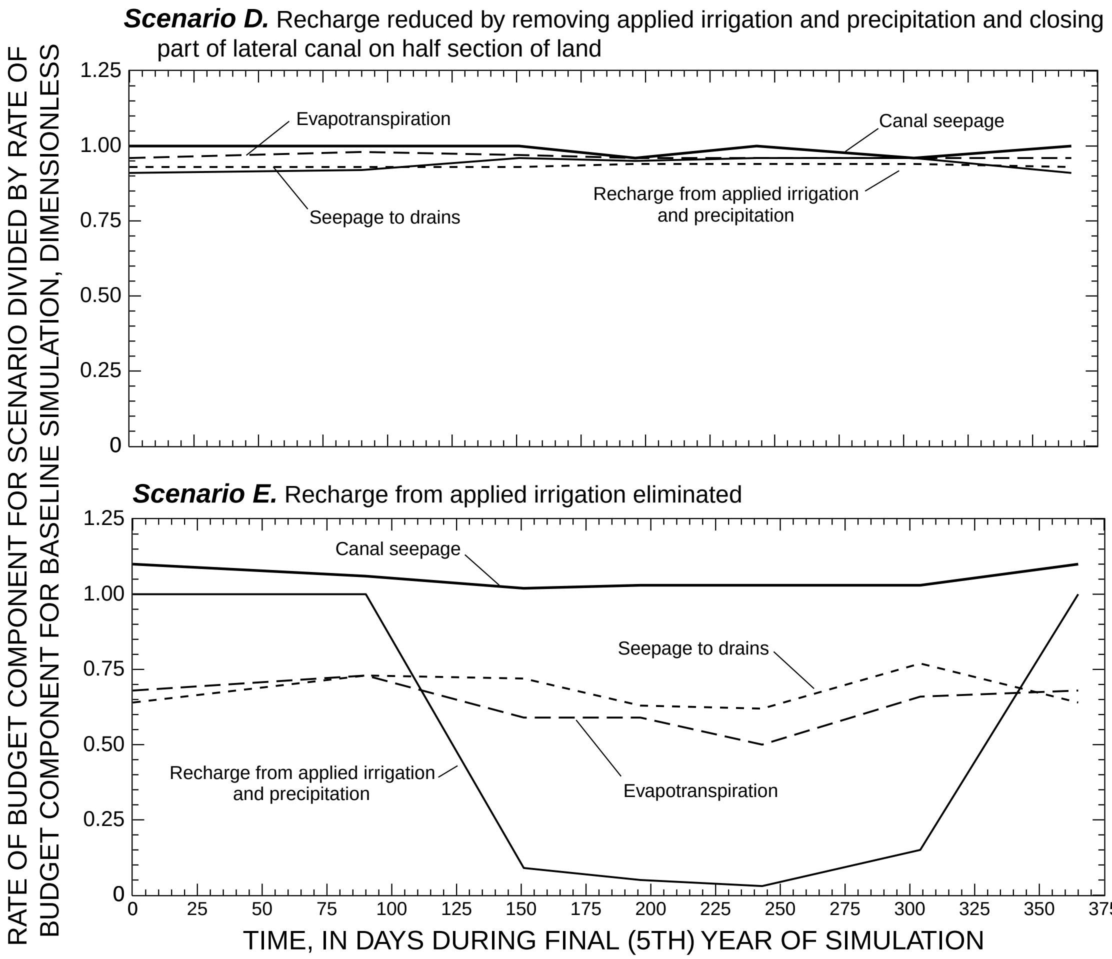


Figure 19. Continued.

discharge to drains (217 acre-ft/yr) than the decrease by ET (154 acre-ft/yr). Closing a section of lateral canal associated with the removal of irrigation from a half section (scenario D) resulted in a decrease in canal seepage of about 193 acre-ft/yr and a slight decrease in the overall ground-water budget when compared with scenario C (table 7). This decrease resulted in a further decrease in seepage to drains and ET (fig. 19*D*).

Simulated Effects in Stillwater Area

Simulated effects on ground-water quantity in the Stillwater area from reducing recharge are discussed in terms of changes in water levels and flow budgets from those of the baseline simulation. Each scenario was simulated for a period of 5 years, which was sufficient to produce a new dynamic equilibrium for each scenario.

Water Levels

Ground-water levels declined from the baseline simulation in each of the five scenarios (table 6; fig. 20). Average water-level declines ranged from 0.1 to 1.4 ft, with the largest average decline simulated when the irrigation season was shortened (scenario B). Except for scenario E, all other scenarios had average declines in head of less than 1 ft. The standard deviation of 1.4 ft or less indicates that most water-level declines in the modeled area were small. Seasonally, largest water-level declines were simulated during summer months (July-Sept.), whereas water-level declines were much less during winter months (Nov.-Mar.; fig. 20).

In scenarios where normal delivery of water in canals was maintained (scenarios A, C, and E; fig. 20*A*, *C*, and *E*), maximum water-level declines of about 4.1 ft or less were simulated in areas most

Table 7. Ground-water budgets for selected scenarios of reduced recharge to shallow aquifer near Fallon and Stillwater, Nevada

[Values are in acre-feet per year, rounded to three significant figures for values greater than 100 and rounded to the nearest acre-foot for values less than 100. Value in parentheses is change relative to baseline simulation. Positive values indicate an increase and negative values indicate a decrease from baseline simulation]

Component	Fallon						Stillwater					
	Baseline simulation	Scenario					Baseline simulation	Scenario				
		A	B	C	D	E		A	B	C	D	E
Inflow												
Recharge from applied irrigation	5,260	2,630 (-2,620)	2,630 (-2,620)	4,910 (-348)	4,910 (-348)	0 (-5,260)	4,540	2,270 (-2,270)	2,270 (-2,270)	4,220 (-321)	4,220 (-321)	0 (-4,540)
Recharge from precipitation	667	667 (0)	667 (0)	630 (-37)	630 (-37)	667 (0)	577	577 (0)	577 (0)	536 (-41)	536 (-41)	577 (0)
Seepage from canals	7,990	8,110 (118)	4,850 (-3,140)	8,010 (13)	7,800 (-193)	8,240 (244)	5,380	5,600 (221)	3,460 (-1,920)	5,400 (17)	5,270 (-113)	5,830 (444)
Seepage from drains	298	459 (162)	344 (47)	298 (0)	298 (1)	645 (348)	881	1,060 (180)	1,230 (348)	876 (-5)	873 (-8)	1,300 (422)
Flow from intermediate aquifer	--	-- --	-- --	-- --	-- --	-- --	76	81 (5)	88 (12)	77 (1)	77 (2)	87 (11)
Total inflow	14,200	11,900 (-2,350)	8,490 (-5,730)	13,800 (-371)	13,600 (-577)	9,550 (-4,670)	11,500	9,590 (-1,870)	7,630 (-3,830)	11,100 (-348)	11,000 (-481)	7,790 (-3,670)
Outflow												
Evapotranspiration	6,500	5,240 (-1,260)	4,280 (-2,220)	6,350 (-154)	6,270 (-229)	3,940 (-2,560)	9,890	8,200 (-1,690)	6,840 (-3,050)	9,540 (-348)	9,420 (-479)	6,470 (-3,420)
Seepage to canals	78	71 (-7)	56 (-21)	78 (0)	78 (0)	66 (-12)	16	14 (-2)	13 (-3)	16 (0)	16 (0)	12 (-4)
Seepage to drains	7,570	6,490 (-1,080)	4,090 (-3,480)	7,360 (-217)	7,220 (-348)	5,480 (-2,090)	1,540	1,370 (-170)	764 (-778)	1,540 (1)	1,540 (-2)	1,300 (-244)
Withdrawals from domestic wells	63	63 (0)	63 (0)	63 (0)	63 (0)	63 (0)	7	7 (0)	7 (0)	7 (0)	7 (0)	7 (0)
Total outflow	14,200	11,900 (-2,350)	8,490 (-5,730)	13,800 (-371)	13,600 (-577)	9,550 (-4,660)	11,500	9,590 (-1,870)	7,630 (-3,830)	11,100 (-348)	11,000 (-481)	7,790 (-3,670)
Change in storage	0	0	1	0	0	3	0	0	0	0	0	0

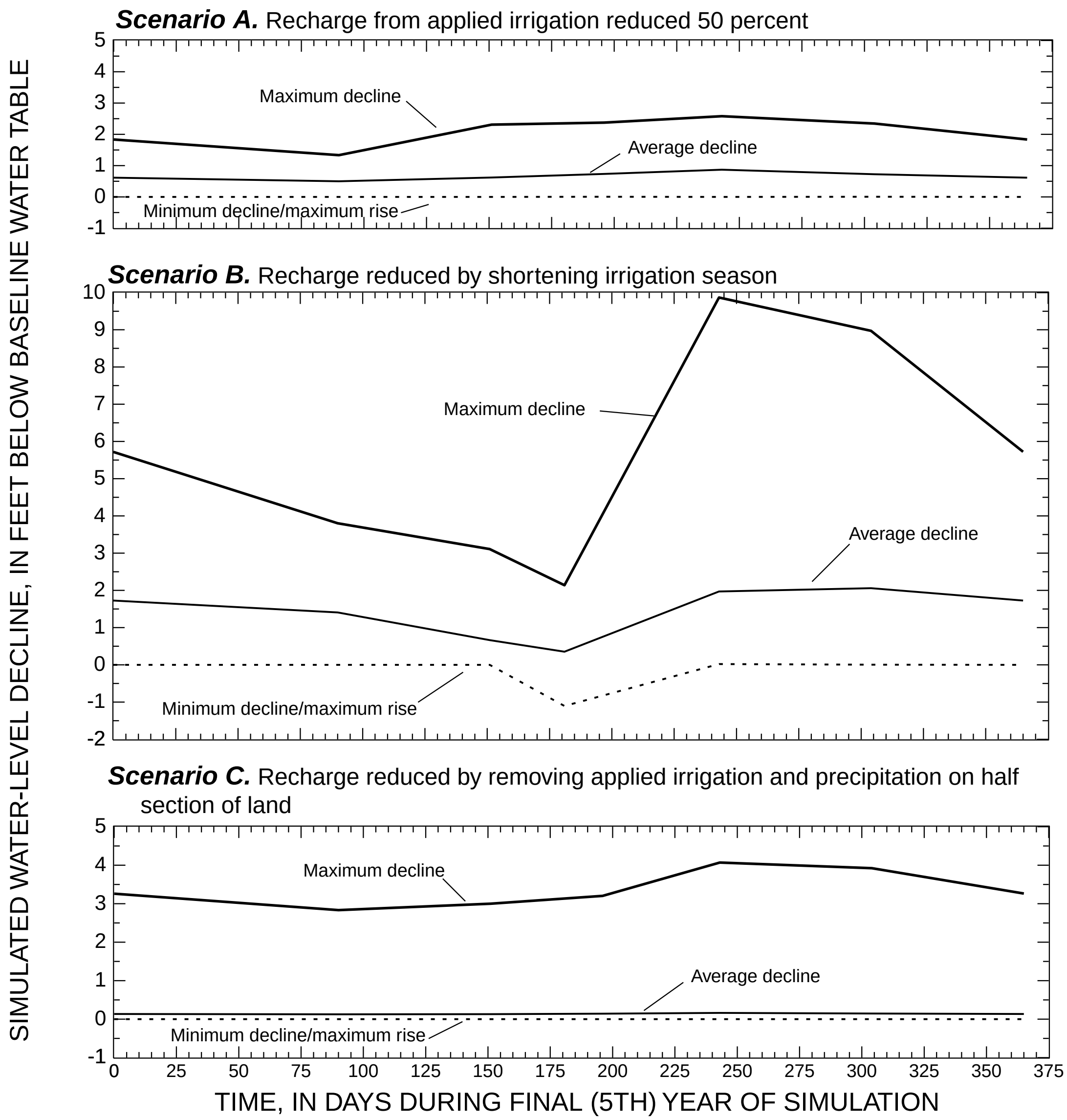


Figure 20. Simulated maximum, average, and minimum water-level declines from baseline simulation for each time period during fifth year for all five scenarios of reducing recharge in model of Stillwater area, Nevada.

distant from a canal. In contrast, a maximum water-level decline of 9.9 ft was simulated near a canal when the irrigation season was shortened (scenario B; fig. 20*B*), and a maximum decline of 7.2 ft was simulated when a section of canal was closed (scenario D; fig. 20*D*). Thus, decreasing the period over which water flows in a canal or closing sections of a canal could produce large water-level declines next to the canal but would have little effect over a large area. In contrast, removing large areas from irrigation would cause a lesser decline in water levels but the decline would occur over a larger area.

Water Budget

Simulated ground-water budget decreased in each of the five scenarios (fig. 21). Changes in ground-water storage between the beginning and end of the fifth year of simulation was near zero for all five scenarios (table 7) indicating that each of these scenarios had reached a new dynamic equilibrium to the simulated changes in irrigation practices.

Decreasing recharge from applied irrigation by 50 percent (scenario A) resulted in a decrease in seepage to drains and ET and an increase in seepage from canals

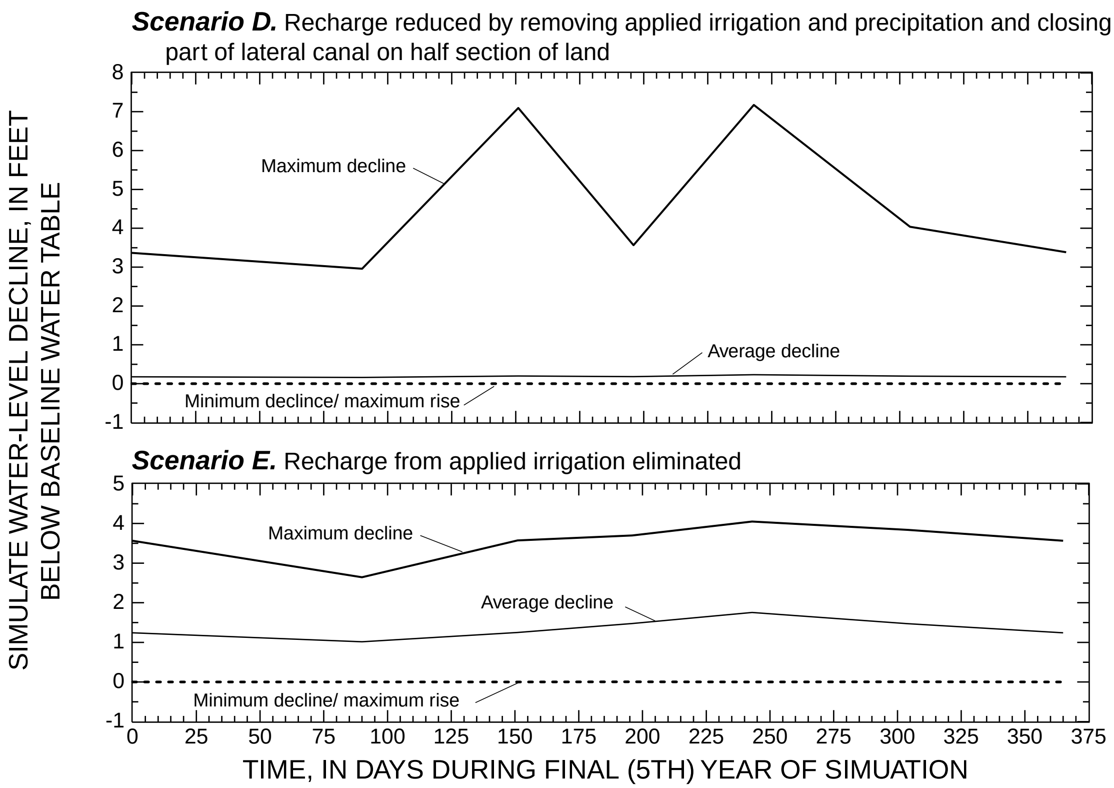


Figure 20. Continued.

and drains (fig. 21*A*). The greatest decrease in the ground-water budget was simulated when the irrigation season was shortened (scenario B; table 7). Shortening the irrigation season greatly reduced canal seepage during the summer months and increased seepage from drains such that it exceeded the ground-water seepage to drains (table 7; fig. 21*B*). These results could be simulated because two drains that enter the modeled area receive water from areas outside of the modeled area. Additionally, upward leakage from the intermediate aquifer increased and downward leakage decreased resulting in a net increase of about 12 acre-ft/yr to the shallow aquifer (table 7). This increase is minimal compared with the overall ground-water budget for the model.

The ground-water budgets were affected least when irrigation for a half section of land was removed (scenario C; fig. 21*C*). Recharge from applied irrigation and precipitation was decreased by about 362 acre-ft/yr, which resulted in a decrease in ET of about 348 acre-ft/yr. Closing the canal associated with the half section of land (scenario D) resulted in a decrease in canal seepage of about 113 acre-ft/yr along with the 362 acre-ft/yr of decreased inflow in scenario C. This removal of the lateral canal in scenario D caused a further decrease in ET when compared with scenario C, but had little affect on the other budget components (fig. 21*D*). Eliminating all recharge from applied irrigation while maintaining water in the canals (scenario E) produced the largest increases from canal and drain seepage compared with the other scenarios (table 7) and also produced the largest decrease in ET of all the scenarios (table 7, fig. 21*E*). However, ground-water seepage to drains did not decrease as dramatically as in scenario B, probably because of the close proximity of drains to canals that maintained their flow during the simulation.

ESTIMATED EFFECTS OF CHANGING IRRIGATION PRACTICES ON GROUND-WATER QUALITY

The possibility that changing irrigation practices will adversely affect water quality in the study area is of concern to residents who depend on wells tapping the shallow aquifer as their sole source of drinking water. Changes in the quantity and type of recharge will result in changes in the quantity of salts added to the

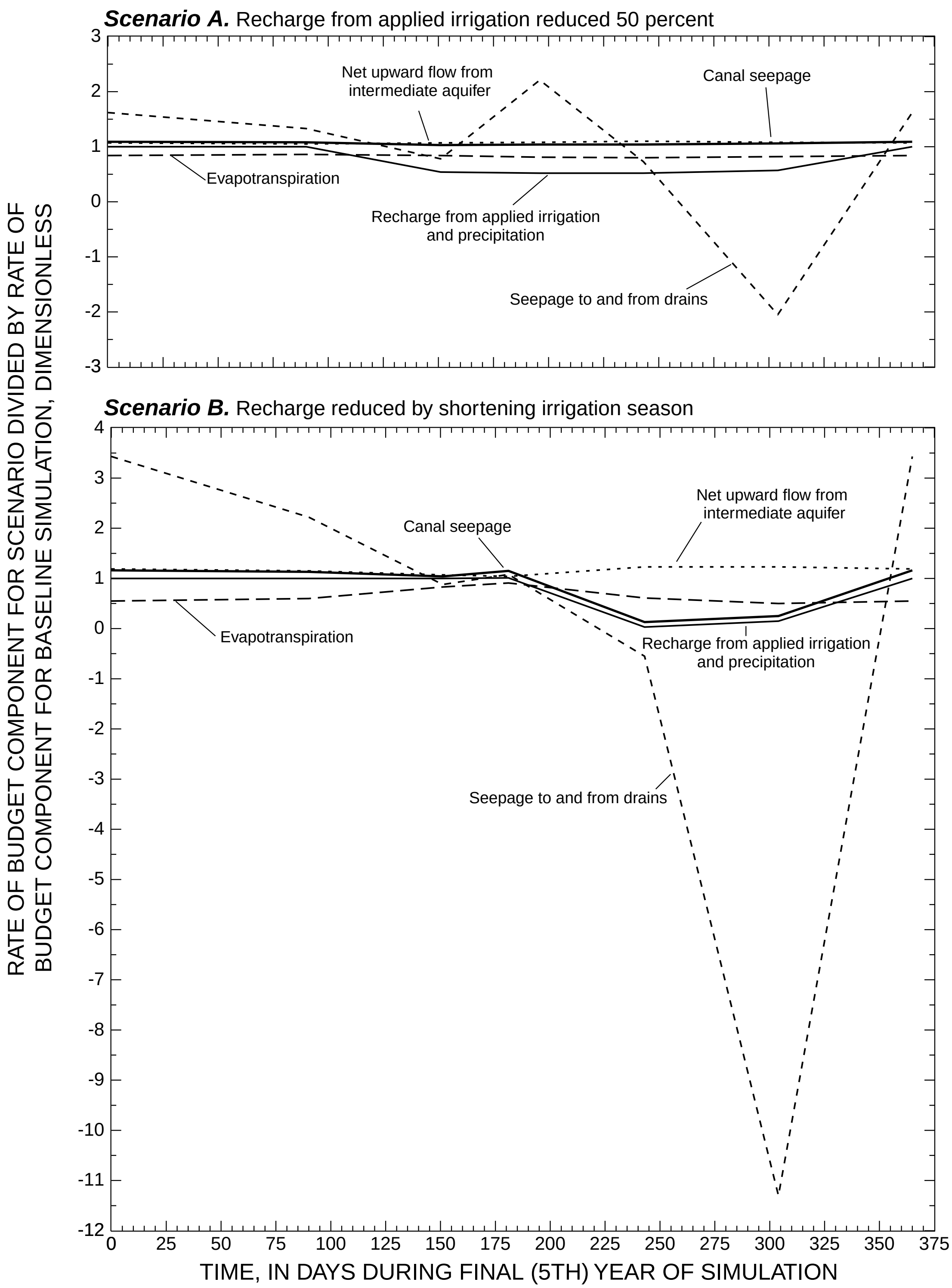


Figure 21. Simulated response of budget components in relation to baseline simulation for each time period during fifth year for all five scenarios of reducing recharge in model of Stillwater area, Nevada. Negative values of seepage to and from drains represent a net change between ground-water seepage to drains and drain seepage to ground water.

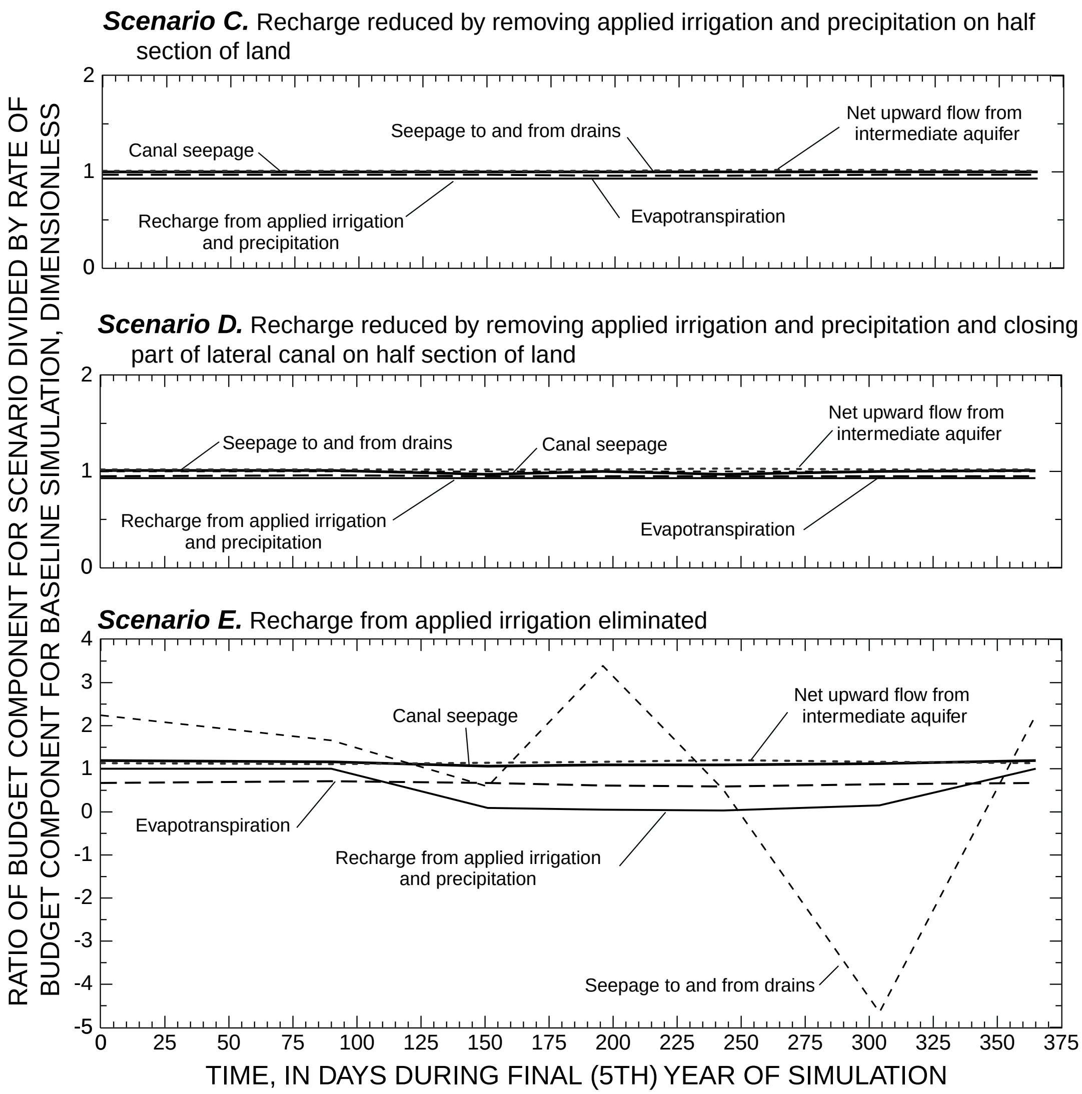


Figure 21. Continued.

aquifer annually and in total dissolved-solids (TDS) concentrations in ground water. The salt load to the aquifer depends on the TDS and quantity of recharge from various sources. A mass-balance approach using results from the simulations was used to estimate the changes in TDS that can be expected as a result of changing irrigation practices.

Quality of Recharge

Ground water originating from canal seepage is of better quality than water originating from infiltration of applied irrigation. Consumption of water by the crops removes water from the soil and leaves behind the salts that were in the water. Water in excess of what plants require must be applied to fields to dissolve and carry these salts away from the root zone so crop production is not diminished. This excess water eventually recharges the shallow ground water.

Water from canal seepage is of better quality because evaporation from canals is less than the ET of water applied to fields. Concentration of TDS in water discharged from Lahontan Reservoir was estimated from specific-conductance measurements made intermittently 44 times at the Carson River gaging station below Lahontan Reservoir (fig. 1). The median specific conductance was 247 μS/cm and the range was from 159 to 941 μS/cm. The median TDS concentration in water discharged from Lahontan Reservoir was estimated based on a relation between specific conductance and TDS concentrations for water in the Carson Desert (Hoffman and others, 1990, p. 30). For specific conductance (SC) less than 5,000 μS/cm the relation is

$$TDS = 0.584 * SC + 22.1 \quad (4)$$

From this equation, the median TDS concentration of water released from Lahontan Reservoir is estimated to be 166 mg/L.

Because of evaporation in the canals, the salinity of water actually applied to the fields will be slightly greater than the water released from Lahontan Reservoir. Between 1995 and 1996, TDS concentration in water from the S-Line Diversion Canal (fig. 2) was measured 15 times; the TDS concentration ranged from 156 to 238 mg/L and the median concentration was 178 mg/L. The S-Line Diversion Canal is a major canal delivering water to agricultural lands in the Fallon and Stillwater areas. A TDS concentration of 180 mg/L is used to represent the quality of canal water in subsequent discussions.

In the general vicinity of Fallon and Stillwater and assuming a year of full irrigation entitlement, about 42 in. (3.5 ft) of water is applied to crops of which about 67 percent (28 in.) is consumed by the crops (Chambers and Guitjens, 1995, p. 437). Because virtually all salts in water applied to fields remains dissolved in the excess water, TDS concentration in water recharging the shallow ground water below irrigated fields is approximately 540 mg/L {180 mg/L * [(42 in.)/(42-28 in.)]}. In 1987-89, TDS concentrations in 13 shallow wells from the agricultural experiment station south of Fallon ranged from 311 to 1,070 mg/L (Lico and Seiler, 1994, fig. 14), and the median concentration was 559 mg/L. A value of 550 mg/L is used to represent the salinity of recharge water from irrigated fields in subsequent discussions because it is midway between the theoretical and measured values.

Salinity of drain water can change greatly over the course of a year in the Newlands Project area. During the non-irrigation season, salinity in drain water typically is higher than during the irrigation season. The greater salinity is because (1) ground-water seepage contributes a larger proportion of the total flow; (2) less dilution occurs because of surface runoff or spills of irrigation water; and (3) seepage from supply canals does not provide water to drains (Lico and Pennington, 1997).

Lico and Pennington (1997) collected samples from 172 drain sites in the Newlands Project area during Feb.-Sept. 1995 to characterize concentrations and loads of potentially toxic constituents in the drain system. Specific conductance ranged from 161 to 3,600 µS/cm for 48 water samples from 30 sampling locations of drains near Fallon (Lico and Pennington, 1997) and the median for the samples was 880 µS/cm. Specific conductance ranged from 220 to 31,800 µS/cm for 30 water samples from 15 sampling locations of drains near Stillwater (Lico and Pennington, 1997) and the median for the samples was 1,080 µS/cm. Using equation 4 to convert specific-conductance measurements to TDS, the median TDS concentrations are 540 mg/L and 650 mg/L for drain water in the Fallon and Stillwater areas, respectively. These concentrations are used to represent the quality of recharge from infiltration of drain water in the areas.

TDS of six water samples from the intermediate aquifer near Stillwater (including geothermal water) ranged from 1,400 to 8,490 mg/L and the median concentration was 4,400 mg/L (Lico, 1992, table 3). The concentration of 4,400 mg/L is used to represent upward flow from the intermediate aquifer to the shallow aquifer.

Atmospheric inputs of salt in dry and wet deposition also were considered. For this analysis, salt carried into the area in wind-blown deposits was assumed equal to that carried out by the wind. TDS in precipitation for the Fallon area was estimated on the basis of chemical analyses of wet deposition near Yerington, Nev., from 1985 to 1994 made for the National Atmospheric Deposition Program/National Trends Network (NADP/NTN). Yerington is about 70 mi southwest of Fallon (fig. 1). Equivalent NADP/NTN data are not available for the Carson Desert area. Concentrations of calcium, magnesium, sodium, sulfate, ammonia, and nitrate were measured in rain and snow. TDS in precipitation is defined as the sum of these constituents. Precipitation-weighted average annual TDS ranged from 1.16 to 3.03 mg/L and the 9-year average was 1.95 mg/L (J.M. Thomas, U.S. Geological Survey, written commun., 1998). After consumption by evapotranspiration, the TDS in recharge water that originated as precipitation is estimated to be 6 mg/L {1.95 mg/L * [(42 in.)/(42-28 in.)]}.

Estimated Changes in Ground-Water Quality

Estimated changes in ground-water quality are described in the following sections relative to changes in quality of water in drains and wells.

Drains

General predictions of how changes in land and water use in the Carson Desert will affect the quality of discharge to drains can be made by using water-quality data and the results of model simulations. The annual salt load to ground water from sources of recharge can be estimated using the equation:

$$\text{Annual Salt Load} = TDS_p{*}R_p + TDS_c{*}R_c + TDS_f{*}R_f + TDS_d{*}R_d + TDS_u{*}F_u \qquad (5)$$

where TDS is total dissolved-solids concentration for each source of water to the shallow aquifer, in milligrams per liter,

R is annual recharge for each surface source, in acre-feet per year, and

F is annual flow between shallow aquifer and intermediate aquifer, in acre-feet per year.

The subscripts denote different sources where

$_p$ is precipitation,
$_c$ is canal seepage,
$_f$ is applied irrigation,
$_d$ is drain seepage, and
$_u$ is upward flow from intermediate aquifer.

Mean salinity of water entering the shallow aquifer from these sources is estimated using the equation:

$$\text{Salinity}_{\text{initial water}} = \text{Annual Salt Load} \div (R_p + R_c + R_f + R_d + F_u) \qquad (6)$$

After consumption of water by ET, the salinity of the ground water (GW) that originated from these sources can be estimated from the equation:

$$\text{Salinity}_{GW} = \text{Annual Salt Load} \div (R_p + R_c + R_f + R_d + F_u - ET) \qquad (7)$$

where ET is loss through ground-water evapotranspiration, in acre-feet per year.

Estimates of average ground-water salinity are only approximate because of the simple method used in equation 7. The estimated value for ground-water salinity from equation 7 does not consider the effects of dissolving salts in the deposits or precipitation of salts at land surface and in near-surface deposits. Also, the quality of water in drains seeping into the shallow aquifer will vary with changes in irrigation practices. If irrigation is greatly reduced, as in scenarios A and E, the quality of water in drains would deteriorate from existing conditions because of less dilution with good quality spill water or surface runoff. This effect may be more important in the Stillwater area than in the Fallon area. Under conditions of reduced irrigation in scenario A, seepage from drains is only 4 percent of the total recharge in the Fallon area but is 11 percent of total recharge in the Stillwater area (table 7).

The value for average salinity of ground water can not be used to estimate water quality in individual drains because quality depends on site-specific hydrology. Drains receiving water derived primarily from canal seepage will be less saline than drains receiving water derived primarily from applied irrigation. Additionally, the distance that water flows through the shallow aquifer from recharge areas to drains and the types of minerals the water passes through also are important in determining drain-water quality.

Fallon Area

The effects of reducing irrigation on average annual salt loads to the aquifer and salinity of ground water were calculated for the Fallon area using recharge and ET rates from the baseline simulation and scenarios A, D, and E (table 7). Water-quality values used are those from previous discussion; 180 mg/L for TDS concentrations in canal water, 540 mg/L for drain water, 550 mg/L for recharge water from applied irrigation, and 6 mg/L for recharge water from precipitation.

Annual salt load to the shallow aquifer in the Fallon area from all sources is estimated at 6,100 tons for the baseline simulation (fig. 22*A*). Of the 6,100 tons, about 64 percent (3,930 tons) is from applied irrigation and about 32 percent (1,950 tons) is from canal seepage. Contributions from precipitation are less than 0.1 percent of the total annual salt load. Average salinity of ground-water recharge for the baseline simulation would be 315 mg/L. In the baseline simulation, ET from the ground water consumes approximately 46 percent of annual recharge (table 4) and after consumption by ET, the average salinity of water discharging to drains would be 580 mg/L. This value is calculated assuming that the only source of salt to the aquifer is recharge beneath fields and canal seepage. The actual salinity of ground water will depend on how much salt is dissolved from minerals in the aquifer and how much mixing there is with existing water.

The effects of reducing recharge from various changes in irrigation practices are compared in figure 22. Removing applied irrigation to fields on a half

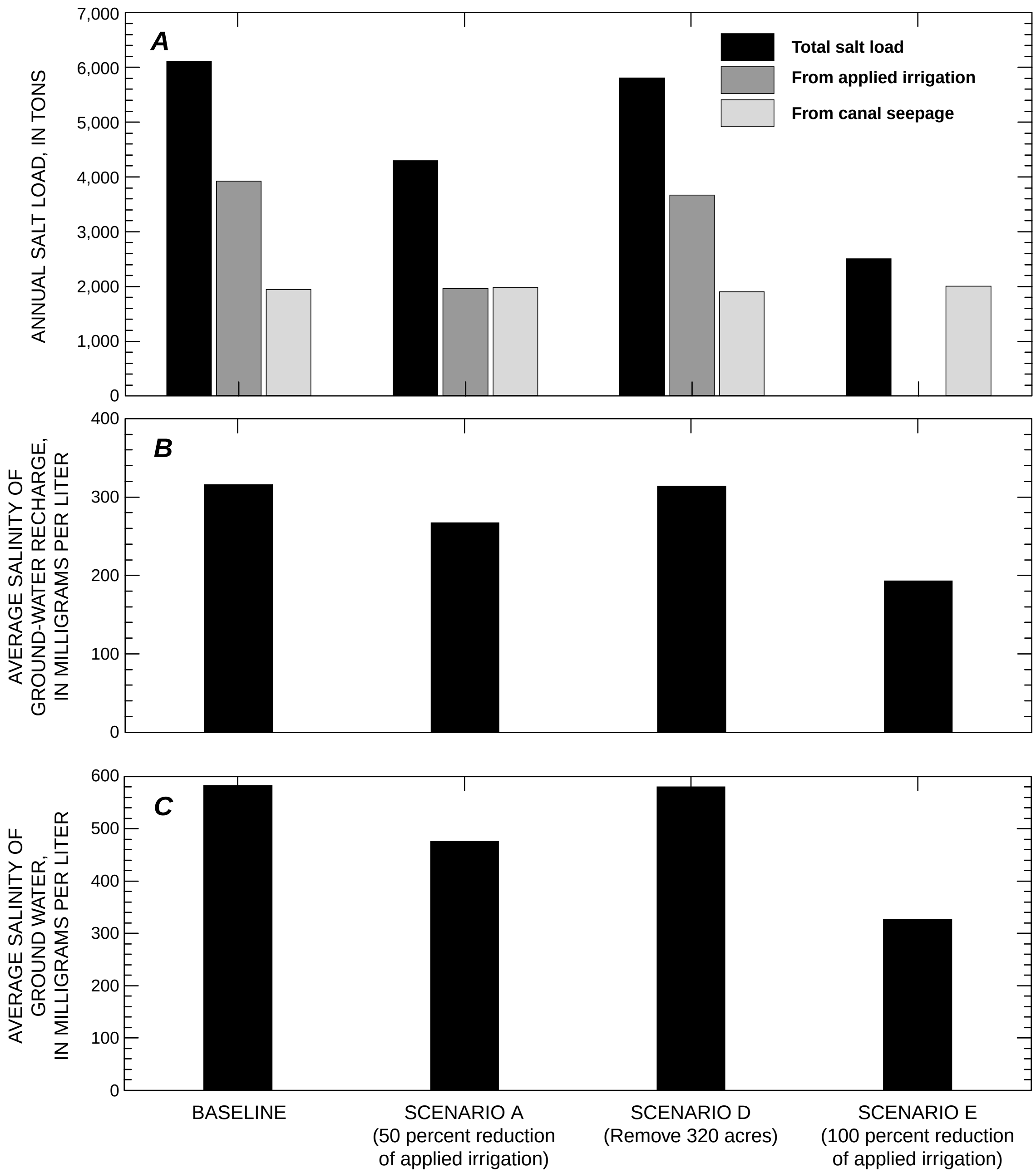


Figure 22. Effects of reducing recharge on salt load, average salinity of recharge water, and average salinity of shallow ground water for scenarios A, D, and E in Fallon area, Nevada.

section of land and closing a section of canal that supplies water to that half section (scenario D) results in only slight changes from the baseline simulation. Reducing applied irrigation by 50 percent (scenario A) reduces the total annual salt load substantially, to about 4,300 tons (fig. 22*A*), of which about 46 percent is from applied irrigation. In this scenario, average salinity of ground-water recharge is reduced to about 270 mg/L (fig. 22*B*). The average salinity of ground water discharging to drains from the shallow aquifer decreases from the baseline simulation of 580 mg/L to 480 mg/L (fig. 22*C*).

In scenario E, recharge of applied irrigation is completely eliminated throughout the modeled area. The elimination of this recharge reduces the annual salt load to about 2,500 tons (fig. 22*A*) and reduces the average salinity of ground-water recharge to about 190 mg/L (fig. 22*B*). The average salinity of ground water discharging to drains under these conditions is about 330 mg/L (22*C*), which is slightly more than one half the concentration of the baseline simulation (580 mg/L).

Stillwater Area

The effects of reducing irrigation on annual salt loads and salinity of ground-water recharge to the shallow aquifer were calculated for the Stillwater area using recharge and inflow rates from the baseline simulations and from scenarios A, D, and E (table 7). Water-quality values used are those from previous discussions. TDS concentrations used were 180 mg/L for canal water, 550 mg/L for recharge water from applied irrigation, 4,400 mg/L for upward flow from the intermediate aquifer, 650 mg/L for drain water, and 6 mg/L for recharge water from precipitation.

Annual salt load from all sources to the shallow aquifer in the Stillwater area is estimated at 6,000 tons for the baseline simulation (fig. 23*A*). Of the 6,000 tons, about 57 percent (3,400 tons) is from applied irrigation, 22 percent (1,300 tons) is from canal seepage, and 20 percent (1,200 tons) is from drain seepage and upward flow of water from the intermediate aquifer. Reducing recharge from applied irrigation to fields by 50 percent (scenario A) reduces the annual salt load to about 4,500 tons (fig. 23*A*), of which about 38 percent is from applied irrigation. Removing applied irrigation in a half section of land and closing a section of canal that supplies water to that half section (scenario D) results in only slight changes from the baseline simulation (fig. 23*A*). Complete elimination of recharge from applied irrigation (scenario E) reduces the annual salt load to about 3,100 tons (fig. 23*A*), of which about 38 percent is from drain seepage and 45 percent is from canal seepage.

The average salinity of ground-water inflow (recharge plus upward flow) for the baseline simulation is 380 mg/L (fig. 23*B*). In the baseline simulation, ET consumes approximately 86 percent of annual ground-water inflow (table 4) and after consumption by ET, the average salinity of water discharging to drains would be 2,800 mg/L (fig. 23*C*). Reducing recharge from applied irrigation by 50 percent (scenario A) causes average salinity of water discharging to drains to decrease to 2,400 mg/L. Completely eliminating recharge from applied irrigation in the modeled area (scenario E) causes average salinity of water discharging to drains to decrease to 1,700 mg/L.

Except in areas very near sources of recharge, reducing recharge by decreasing irrigation in the Stillwater area should not change water quality in the shallow aquifer. Even high quality water from canal leakage rapidly becomes saline because all of the salts originally in the shallow ground water become concentrated in a small volume through ET. Additionally, upward flow from the intermediate aquifer, which is present only in the Stillwater area, contributes substantial quantities of salts to the shallow aquifer.

Wells

Estimating changes in water quality in drains is much easier than estimating changes in water quality in wells because drains integrate changes over larger areas. Estimating changes in wells is more difficult because of uncertainty in what area contributes to a well and because detailed knowledge of the quality of shallow ground water in the contributing area is required. In the shallow aquifer, estimating quality of water from a well is difficult because of the heterogeneity of the deposits. The quality of water in the shallow aquifer can be substantially different between wells less than 100-ft apart (Lico and others, 1987; Lico and Seiler, 1994). Furthermore, quality of ground water in the finer-grained deposits commonly is different from that in the coarser-grained deposits (Lico and Seiler, 1994).

Ground-water flow and water quality in the shallow aquifer are largely determined by flow in the coarser-grained channel deposits. Water from a well intersecting a channel deposit is likely to be of better

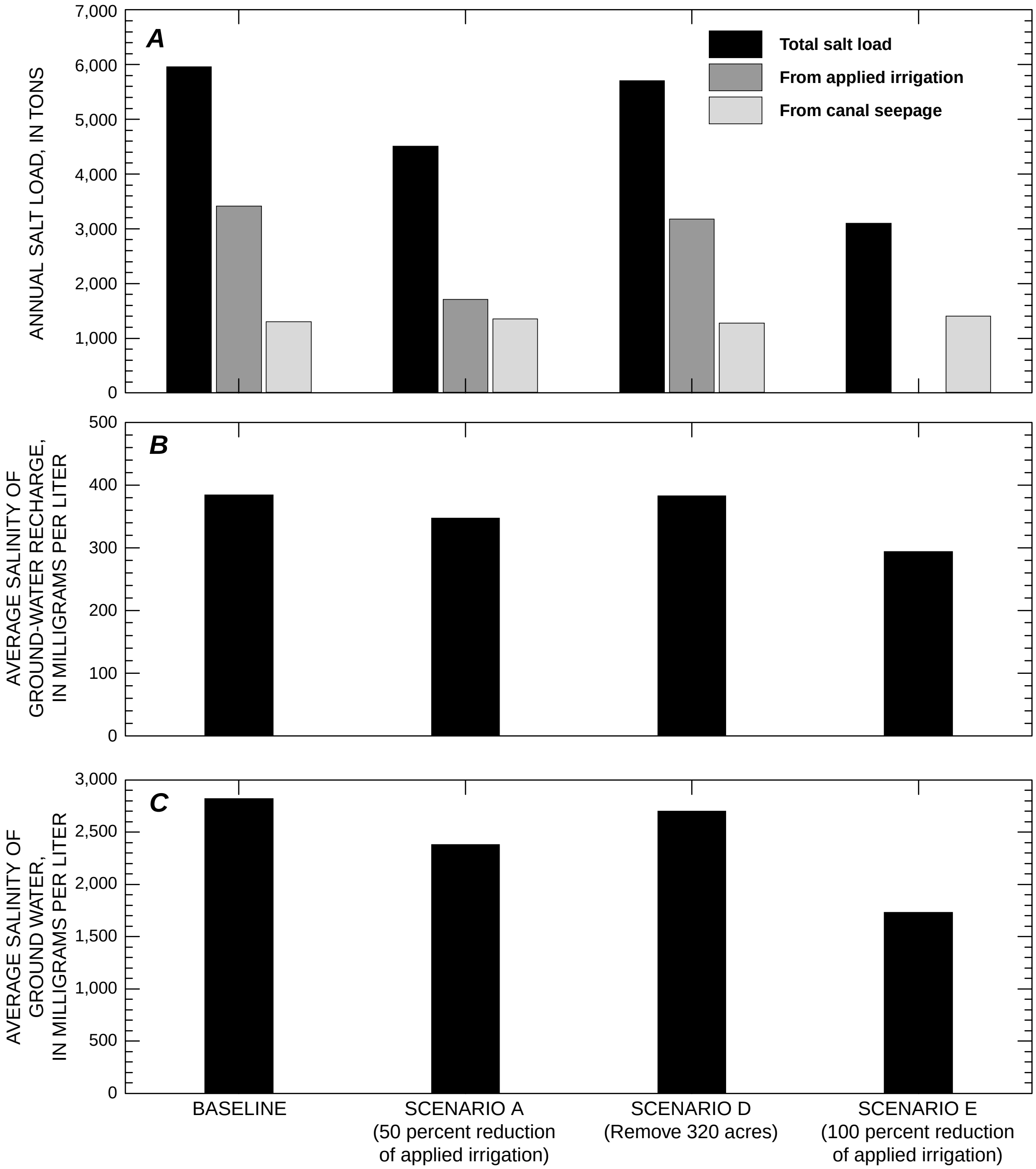


Figure 23. Effects of reducing recharge on salt load, average salinity of recharge water, and average salinity of shallow ground water for scenarios A, D, and E in Stillwater area, Nevada.

quality than water from a nearby well that does not intersect a channel deposit. The source of water in a well screened in a channel deposit may be seepage from a canal into channel deposits distant from the well. Water applied to a field underlain by channel deposits may not become as saline because less of the percolating water is lost through ET. Additionally, water moves more rapidly through channel deposits, resulting in less time for dissolution of minerals from the deposits.

Over time, shallow wells have been located to optimize the quantity and quality of water withdrawn from them. Wells that penetrated only fine-grained deposits or salty water are abandoned and replaced with another in an attempt to obtain better water. Past experience of landowners and drillers guided well siting for the replacement wells. This optimization likely has resulted in most wells being dependent on their proximity to canals or channel deposits.

Water quality in some wells in the shallow aquifer is likely to deteriorate as a result of land and water use changes. Changes in land and water use, such as closing of a lateral canal from service, can mean a once optimal location may no longer be optimal for obtaining the best quality water. What happens at a specific well largely depends on its relation to channel deposits, distance from principal canals, and specific well construction details such as its depth and open interval. The following discussion is intended to provide a general description of the types of changes that may be expected.

Closing canals and laterals from service because they are no longer needed to provide water to fields will affect wells tapping high quality water originating as canal seepage. When recharge from a canal or lateral is removed, lower quality water (such as that under fields) may become the principal source of water withdrawn by the well.

Declines in water level caused by changes in land and water use can result in lowered water quality. Although water-level declines may be small on a large scale, water-level declines of several feet may exist in the immediate vicinity of a field or canal taken out of use. These declines can change local flow paths, such that the principal source area for a well may change to an area with lower quality water.

The Stillwater area is a discharge area (Seiler and Allander, 1993; Maurer and others, 1996), and higher concentrations of TDS are expected in the ground water because of upward movement of saline water from depth. Simulation results indicate that, as less water is applied to the fields in the Stillwater area, greater inflow from more saline sources, such as seepage from drains and upward flow from the intermediate aquifer, becomes a larger component of the ground-water flow budget (table 7). Water quality can be expected to deteriorate because of increased flow from these more saline sources. Salinity of ground water in the Stillwater area is likely to exceed drinking water standards for all areas except those very near sources of canal seepage. Elsewhere, water that recharges the shallow aquifer from infiltration of applied irrigation is discharged nearby by ET.

In wells near major canals, the water quality likely will be unaffected as a result of changes in land and water use in the vicinity of the well, as long as such changes do not affect how a canal is used. A change in water use from agricultural to maintenance of wildlife habitat may not affect canal use because water still must be conveyed from Lahontan Reservoir to wildlife areas near Carson Lake and the Stillwater National Wildlife Refuge (fig. 1).

Trace-Element Concentrations

Arsenic and uranium concentrations exceeding 100 µg/L are widespread in shallow ground water in the Carson Desert and locally exceed 1,000 µg/L (Welch and Lico, 1998, p. 536). Arsenic concentrations exceeding 20,000 µg/L were reported from small surface ponds near the Stillwater Wildlife Management Area (Tuttle and Thodal, 1998, table 10). Changes in aquifer redox conditions, and ground-water flow paths following changes in irrigation practices may affect trace-element concentrations in some wells.

Concentrations of arsenic, and other trace elements, in the Carson Desert are highly variable and controlled by local redox conditions in the aquifers (Lico and Seiler, 1994). Changes in redox conditions in the aquifer brought about by a change in recharge from irrigation could cause trace-element concentrations to either increase or decrease, depending on the trace element. Infiltration of irrigation and canal water carries oxygen into the subsurface. Decreasing the quantity of water and hence, decreasing the quantity of oxygen to the shallow aquifer may result in reducing conditions developing in the aquifer, particularly in areas where sufficient organic matter exists to consume the oxygen.

Iron and manganese oxides commonly form on grains in the presence of dissolved oxygen (Welch and Lico, 1998) and arsenic binds to these oxides.

Welch and Lico (1998) concluded that the iron and manganese oxides likely are sources of arsenic in the Carson Desert. Under reducing conditions these oxides become soluble and release iron, manganese, and trace elements such as arsenic that are bound to the oxides. Thus, iron, manganese, and arsenic concentrations may increase in water withdrawn from some domestic wells as a result of reduced recharge from changing irrigation practices. Uranium concentrations, on the other hand, may decrease because uranium becomes less soluble under anoxic conditions.

Trace-element concentrations may change in some wells because of changes in paths of ground-water flow causing a change in the quantity of water withdrawn from different sources. As noted previously, water quality in the shallow aquifer can change greatly over short distances. Changes in the quantity and location of recharge could change localized flow paths sufficiently enough that the well begins to tap nearby water rich in trace elements that currently do not contribute to the well.

SUMMARY AND CONCLUSIONS

The Newlands Project was built in the early 1900's to supply water for irrigation to land in the Carson Desert near Fallon, Nevada. An aspect of the project was the diversion of water from the Truckee River upstream of Pyramid Lake to Lahontan Reservoir, on the Carson River. Public Law 101-618 was passed in 1990 for the purpose of increasing flow in the Truckee River to Pyramid Lake and increasing flow in the Carson River to wetlands in the Carson Desert. Recent efforts by environmental groups and the U.S. Fish and Wildlife Service to purchase agricultural water rights in the area have caused concern regarding the viability of the shallow aquifer used as a water supply by residents. The reduction of recharge caused by the purchase of agricultural water rights could affect the quantity of water in the shallow aquifer which is used for domestic supply. Many residents have voiced concern over the potential effects reducing irrigation may have on their water supply. Thus, the U.S. Geological Survey began a cooperative study with the Bureau of Reclamation in Dec. 1996 to estimate potential effects of changing irrigation practices on reducing recharge to the shallow aquifer in the Newlands Project area.

Ground water is present at shallow depths over large areas of the Carson Desert. Depth to water is generally less than 25 ft below land surface over much of the valley floor and generally less than 10 ft beneath much of the irrigated areas. The more uniform depth to ground water is controlled largely by the gently sloping terrain, recharge beneath irrigated fields, seepage from an extensive network of canals, and discharge from ET and seepage to drains. Several aquifers have been delineated beneath the Carson Desert. The principal aquifers are the shallow and intermediate aquifers in unconsolidated sedimentary deposits, a deep aquifer in the unconsolidated to semiconsolidated sedimentary deposits, and a basalt aquifer. The shallow aquifer generally is used as the principal water supply in areas not serviced by the City of Fallon.

The shallow aquifer is of concern because reduction in irrigation will have the greatest effects on its water supply. The shallow aquifer is characterized by abrupt changes in lithology and water quality, both vertically and horizontally. The abrupt changes in lithology result from a complex mixture of river-channel, delta, floodplain, shoreline, lakebed, and sand-dune deposits. Generally, these sediments in the shallow aquifer are coarser and more permeable west of Fallon and become finer grained and less permeable to the east.

The direction of flow in the shallow aquifer follows the general direction of flow in the Carson River. Locally, shallow ground-water flow is controlled by the location of canals and drains and by applied irrigation to fields. Water levels in the shallow aquifer fluctuate in response to when water is released to canals and when fields are irrigated. Near irrigated areas, water levels fluctuate seasonally between 2 ft and 6 ft below land surface with highest water levels during the irrigation season (Apr.–Oct.) and lowest water levels during winter (Nov.–Mar.). The decline in water levels during the winter generally is limited to the depth of drains, which have been excavated between 4 ft and 8 ft below fields in most areas but can be as much as 20 ft in some areas. Water levels in areas distant from stream channels and irrigation fluctuate less than 2 ft seasonally.

Hydraulic conductivity of the shallow aquifer is highly variable. Estimates of hydraulic conductivity from slug-test analyses range from 0.01 to 900 ft/d and estimates from specific-capacity data range from 6 to 480 ft/d. Geometric mean hydraulic conductivity is 4 ft/d for the 17 estimates from slug tests and 45 ft/d for the 69 estimates from specific-capacity data. Estimates of hydraulic conductivity from specific-capacity data were divided into two groups to represent the finer sand of interchannel deposits and coarser sand of channel deposits. The geometric mean hydraulic conductivity for interchannel deposits is 22 ft/d and for channel deposits is 136 ft/d. Both estimates only represent the more permeable deposits within the shallow aquifer.

The potential effects of reducing recharge to the shallow aquifer were estimated using numerical models of ground-water flow of two representative areas in which removal of irrigation could be evaluated in terms of changes in ground-water levels, flow, and water quality. Two areas, each about 9 mi^2 (5,760 acres), were selected on the basis of having large canals and drains as boundaries along at least two sides. The first area selected is just south of Fallon, Nev., where vertical gradients in the unconsolidated alluvial deposits indicate mostly lateral flow through the sedimentary aquifers. The second area selected is near Stillwater, Nev., where vertical gradients indicate upward flow through the sedimentary aquifers.

Numerical models were constructed for the shallow aquifer in each area. One model layer was used to represent flow in the Fallon area. For this model no flow is assumed between the shallow and intermediate aquifers. In contrast, two layers were used to represent flow in the Stillwater area. The second layer was used to simulate upward flow from the intermediate aquifer into the shallow aquifer. Both models were used to simulate the general timing and duration of recharge for a typical year. Results for a typical year were then used to determine the effects of reduced recharge from canals and applied irrigation on water levels, flow, and water quality caused by changing irrigation practices. The models are not intended to be exact replicates of flow in the shallow aquifer, instead the models were designed to simulate general effects caused by decreasing applied irrigation in the representative areas near Fallon and Stillwater.

Each model was calibrated to general conditions because records of changes in water levels in the shallow aquifer and on the timing and quantity of water delivered to individual farms were insufficient. The general conditions are based on typical irrigation practices during the course of a normal year. The normal year was divided into six periods to represent changing irrigation practices. The normal year was then repeated for 5 years during calibration because exact initial conditions were not known. The 5-yr period was sufficient to attenuate effects caused by the initial conditions.

The models were calibrated by changing the hydraulic properties, the vertical hydraulic conductivity used to simulate flow between surface water and ground water, and the extinction depth of ET. During calibration, modeled values were adjusted within acceptable limits until simulated water levels approximated observed ground-water levels and gradients in both areas, and inflow and outflow approximated estimated rates. For the Fallon area, hydraulic conductivity of interchannel deposits was 10 ft/d and channel deposits was 100 ft/d. These values were decreased in the Stillwater area to 5 and 50 ft/d, respectively, to account for a greater percentage of fine-grained deposits in the area. A specific yield of 0.20 for interchannel deposits and 0.26 for channel deposits was used in the simulations and was calibrated on the basis of seasonal water-level fluctuations.

Results from the model simulations indicate that canal seepage and applied irrigation account for most of the recharge in the modeled areas. Simulated inflow in the Fallon area was 14,200 acre-ft/yr; whereas, simulated inflow in the Stillwater area was 11,500 acre-ft/yr. Lateral subsurface flow from outside the modeled areas account for less than 1 percent of the inflow and thus, were not included in the simulations. Outflow of ground water primarily is by discharge from ET and seepage to drains in the Fallon area and by ET in the Stillwater area. Much of the ground-water flow that discharges to drains is through the more permeable channel deposits. Although average ground-water flow in the shallow aquifer can be estimated using average hydraulic properties, the distribution of the channel deposits is important to understanding paths water may take in a particular area.

Five scenarios (A-E) were simulated to estimate the possible effects of changing irrigation practices in the Fallon and Stillwater areas on ground-water levels and flows in the shallow aquifer. Model results also were used to estimate effects on ground-water quality. In each scenario, the quantity of applied irrigation water was reduced from a normal irrigation season.

The results of each scenario were compared with those from the baseline (calibrated) simulation of each area. (1) In scenario A, recharge from applied irrigation was reduced by 50 percent throughout each modeled area while maintaining the full delivery of water in canals. (2) In scenario B, the irrigation season was shortened to simulate a reduction of 50 percent in water applied to fields. Besides decreasing applied irrigation, water deliveries in canals ceased at the end of the shortened irrigation season. These simulations were to determine the effect caused by a prolonged reduction of water over each area. (3) In scenario C, applied irrigation of a half section (total area of 320 acres) was removed in the middle of each modeled area. Because not all land in a half section is irrigated, the acreage in which irrigation ceased varied from 292.5 acres near Fallon to 275 acres near Stillwater. (4) Scenario D is the same as scenario C except that a section of a lateral canal associated with the half section of land also was closed. These scenarios were to estimate effects caused by reducing the number of acres irrigated in an area. (5) In scenario E, all recharge from applied irrigation fields was eliminated, while recharge from precipitation and water deliveries in the main and lateral canals were maintained. Although maintaining water in the lateral canals is unlikely if all irrigation in an area ceases, the scenario provides an estimate of the effects of eliminating recharge from applied irrigation to fields over an area larger than a half section.

Each scenario was simulated for a period of 5 years, which was sufficient to reach a new dynamic equilibrium. Water-level declines for all scenarios averaged 1.1 ft or less in the Fallon area and 1.4 ft or less in the Stillwater area. Greatest water-level declines of about 10 ft were simulated in both modeled areas near canals following the shortened irrigation season (scenario B). When all recharge from applied irrigation was eliminated in both modeled areas while maintaining water in canals (scenario E), maximum declines of 4 ft in the Stillwater area and 7 ft in the Fallon area were simulated beneath fields distant from canals.

The ground-water budget decreased less than 5 percent in both modeled areas when irrigation on a half section was eliminated (scenarios C and D). The greatest decease in the ground-water budget was simulated when the irrigation season was shortened (scenario B). The budget decreased 40 percent in the Fallon area and 33 percent in the Stillwater area. In this scenario, recharge from canal seepage decreased due to the shortened irrigation season, consequently, seepage to drains decreased as well as discharge by ET. In the Stillwater area, net upward flow for the baseline simulation was about 76 acre-ft/yr, this flow increased at most 12 acre-ft/yr in scenario B, which is negligible compared with the other components of the ground-water budget.

Estimates of salt loads from mass-balance calculations indicate that, for a typical irrigation season, recharge from precipitation, canal seepage, and infiltration of applied irrigation contributes about 5,900 tons of salts annually to the Fallon area and 4,700 tons to the Stillwater area. Seepage of water in drains and upward flow of saline water from the intermediate aquifer contributes an additional 1,200 tons of salt to the Stillwater area. Results of simulated changes in flow caused by eliminating irrigation on parcels as large as a half section causes only small changes in annual salt load to the shallow aquifer.

In the baseline simulation of the Fallon area, about 64 percent of the annual salt load is from applied irrigation with canal seepage providing most of the remainder. Reducing the quantity of applied irrigation by half while maintaining water deliveries in the canals, results in reducing the average salinity of ground water from 580 to 480 mg/L.

In the baseline simulation of the Stillwater area, about 57 percent of the annual salt load is from applied irrigation with canal seepage providing about 22 percent. Other sources of salts are drain seepage and upward flow of saline water from the intermediate aquifer. Evapotranspiration consumes approximately 86 percent of all inflow, hence total dissolved solids in ground water near the water table can be high, because salts are concentrated into a small volume of water.

Estimating the effects at individual wells is difficult because of the heterogeneity of deposits and water quality in the shallow aquifer. Over time, shallow wells in the Fallon area have been located to optimize the quantity and quality of water withdrawn from them. In the future, what was once an optimal location for a well may no longer be optimal for obtaining the best quality water. Such optimization of well location likely has resulted in most wells that now tap good-quality water being dependent on their proximity to canals and channel deposits. Abandoning sections of canals likely will affect the water quality in wells whose source primarily is seepage from a canal. As canal seepage decreases, poor-quality water from surrounding deposits in the shallow aquifer may move slowly into the more permeable deposits.

Model simulations indicate that ground-water levels and flows in the shallow aquifer will not be affected greatly unless water deliveries in canals are reduced. However, actual changes can be evaluated by periodically sampling water in drains and wells near affected areas.

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